The origin of the elements in the Universe

Particles In Collisions
Arica, 10-13 October 2023

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INFN - Laboratori Nazionali del Gran Sasso
on behalf of the LUNA collaboration

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Nuclear Astrophysics

What is the Universe made of?

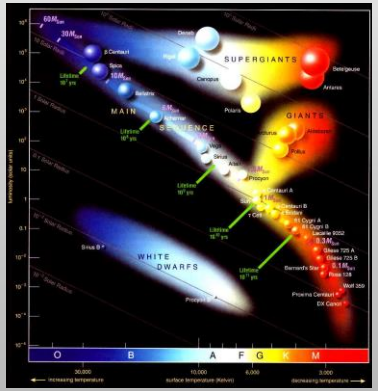
Where do elements come from?

How do nuclear reactions take place?

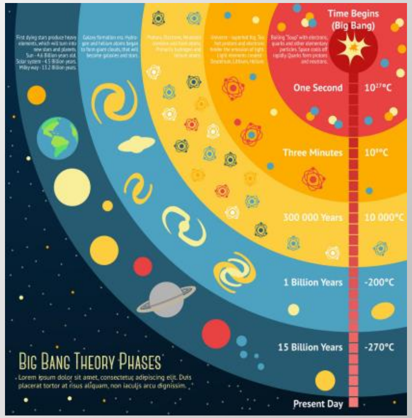
Challenges of Nuclear Astrophysics

Experimental methods

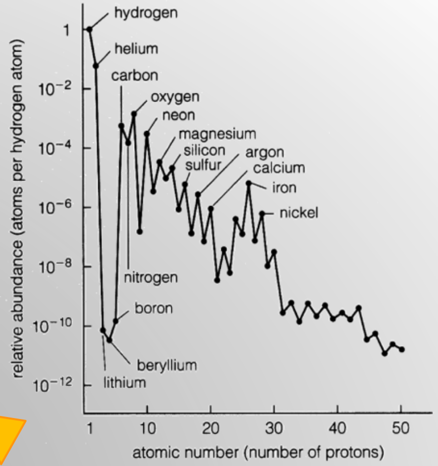
Stellar evolution



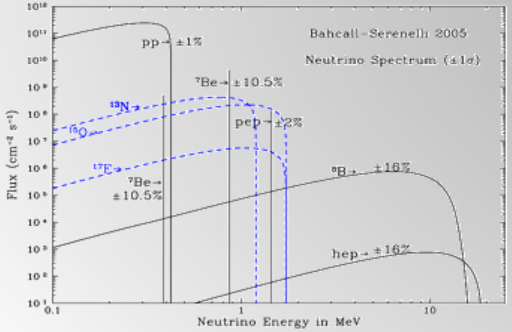
Astroparticle physics



Nucleosynthesis

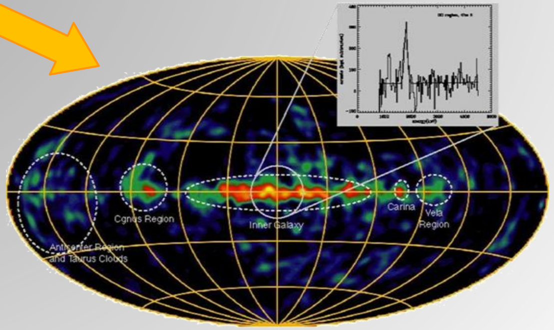


Nuclear astropysics



Solar neutrinos

Solar system



(Oberlack et al., 1996; Pluschke et al., 2001)

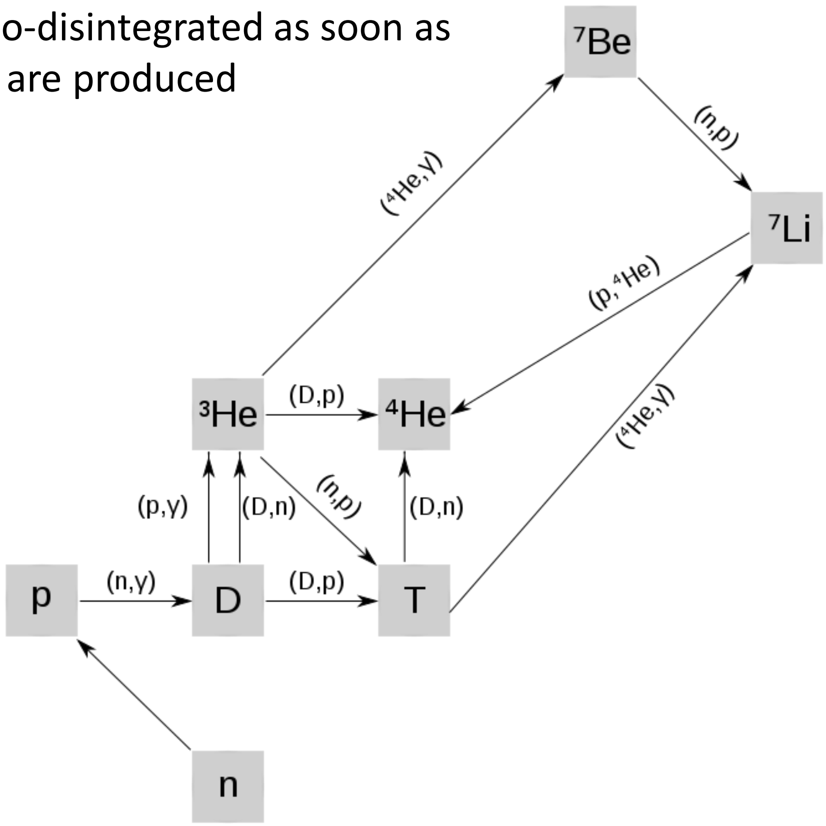
Astronomy

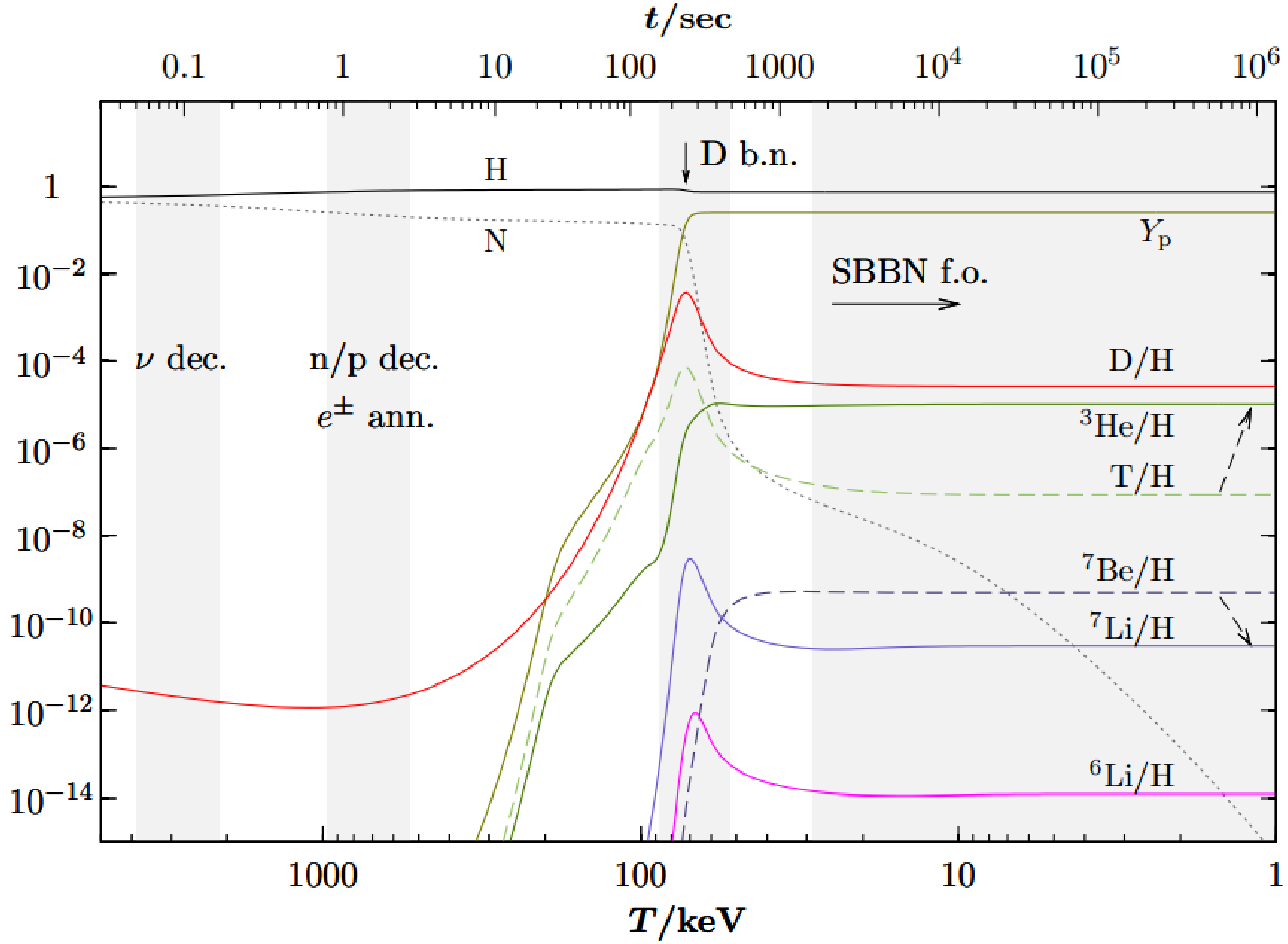
How nucleosynthesys begins (long story short…)

Time after Big Bang	Temperature [K]	Key Events
0 - 10^{-43} s	∞ - 10^{32}	Big Bang – Planck epoch. Physics can not yet describe this time.
10^{-43} s	10^{32}	Gravitational force separates from the strong-electro-weak force.
10^{-35} s	10^{27}	The strong force separates from the electro-weak force. Inflation occurs? Universe expands by factor of 10^{25}. Quarks, leptons and gluons were present.
10^{-12} s	10^{15}	Electroweak symmetry breaking (four fundamental forces now distinct). Leptogenesys and baryogenesis. Gravity starts to control expansion.
10^{-6} s	10^{13}	Quarks and anti quarks form protons, neutrons and antiparticles. Protons and antiprotons, neutrons and antineutrons annihilate each other leaving slight excess of protons and neutrons plus lots of photons. The temperature is still too high to allow nucleosynthesis.
0.1-1 s	**10^{10}**	**n/p ratio freezes-in ($\simeq 0.21$)** **Temperature is now sufficiently low to allow nucleosynthesis.**

Big Bang Nucleosynthesys (BBN)

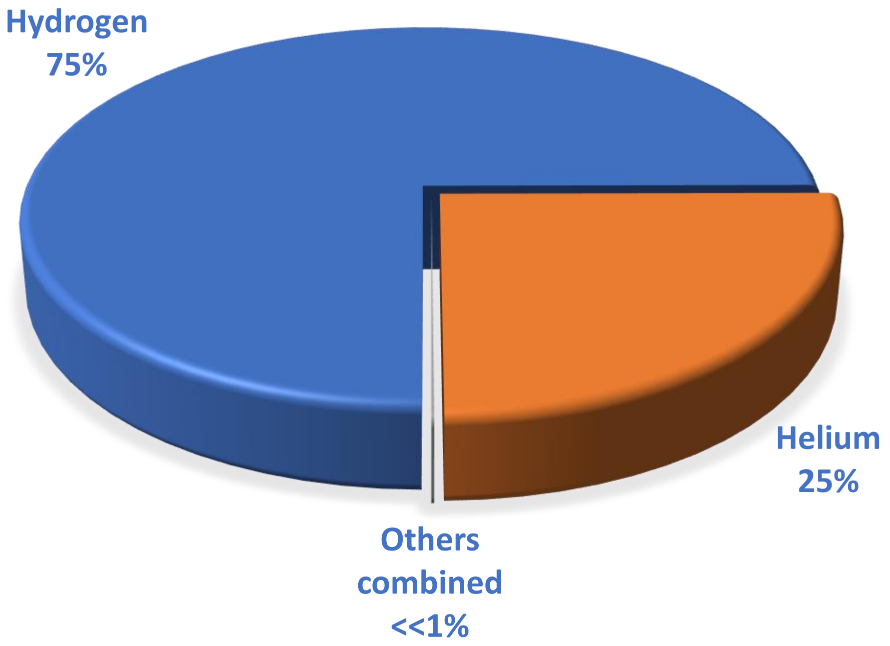
heavier nuclei are not anymore photo-disintegrated as soon as they are produced





Composition of the early Universe

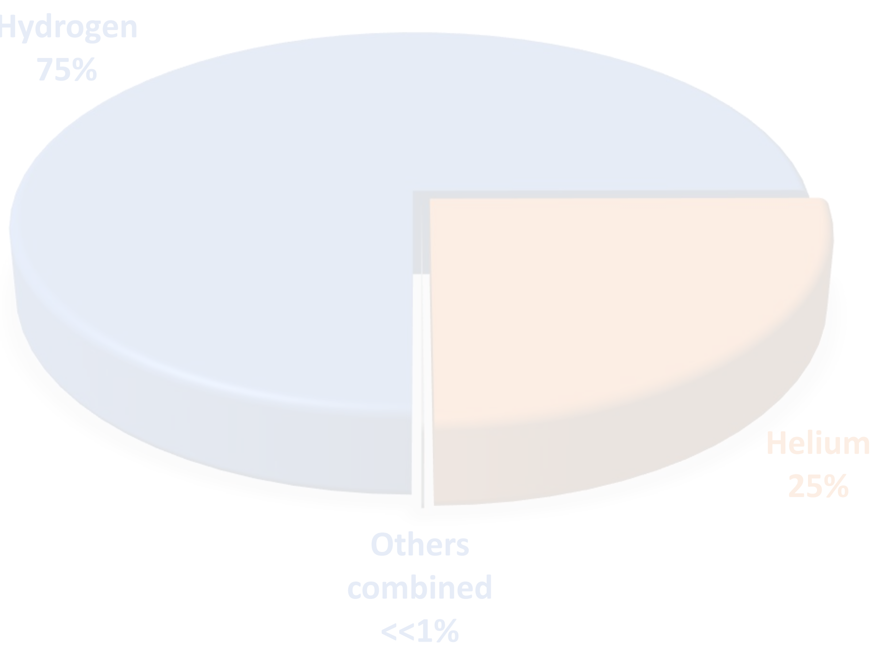
The Universe
3 minutes after the Big Bang



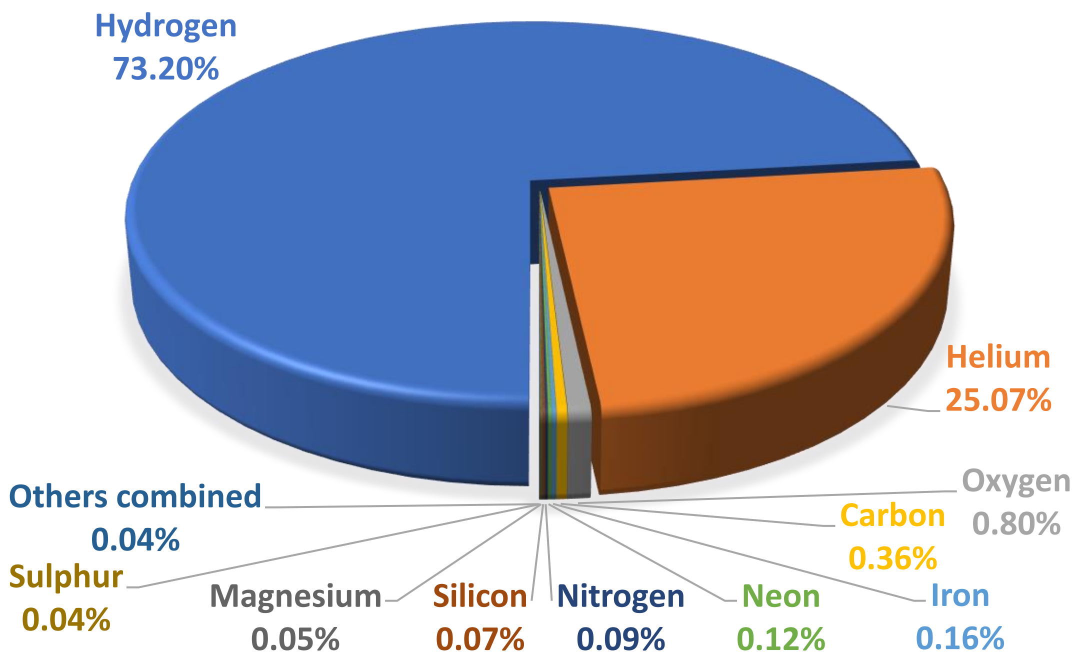
There were no stars
nor planets yet

Composition of the present Universe

The Universe
3 minutes after the Big Bang



The Sun
today



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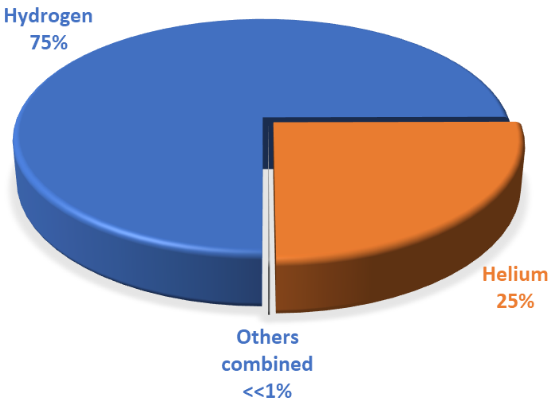
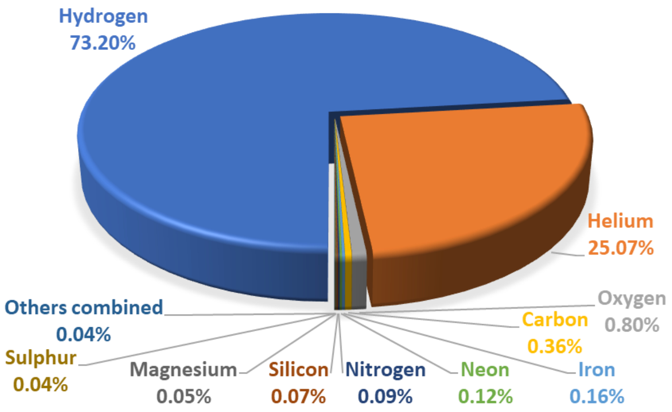
What causes the composition to change?

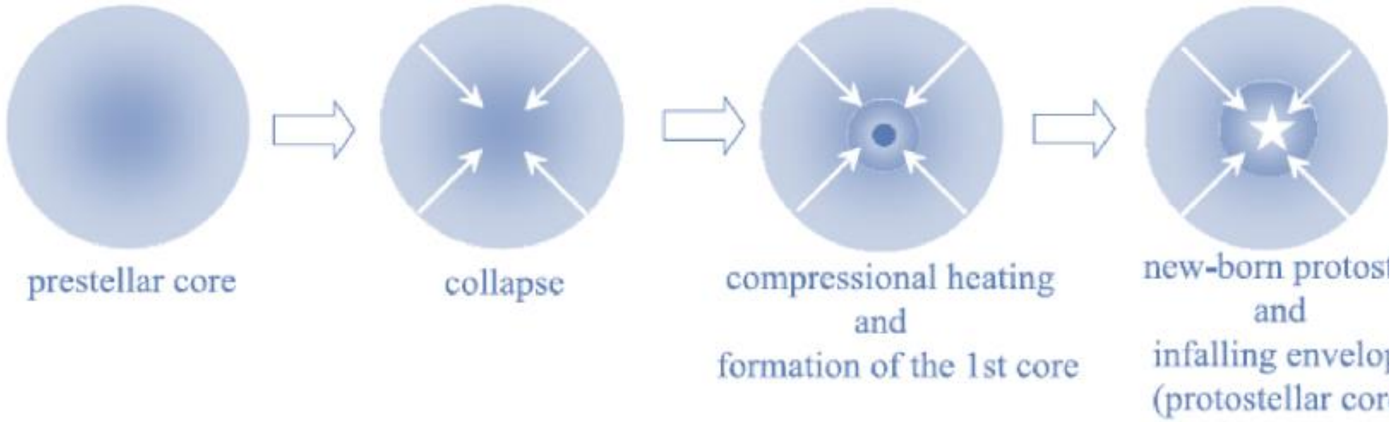
The Universe
3 minutes after the Big Bang

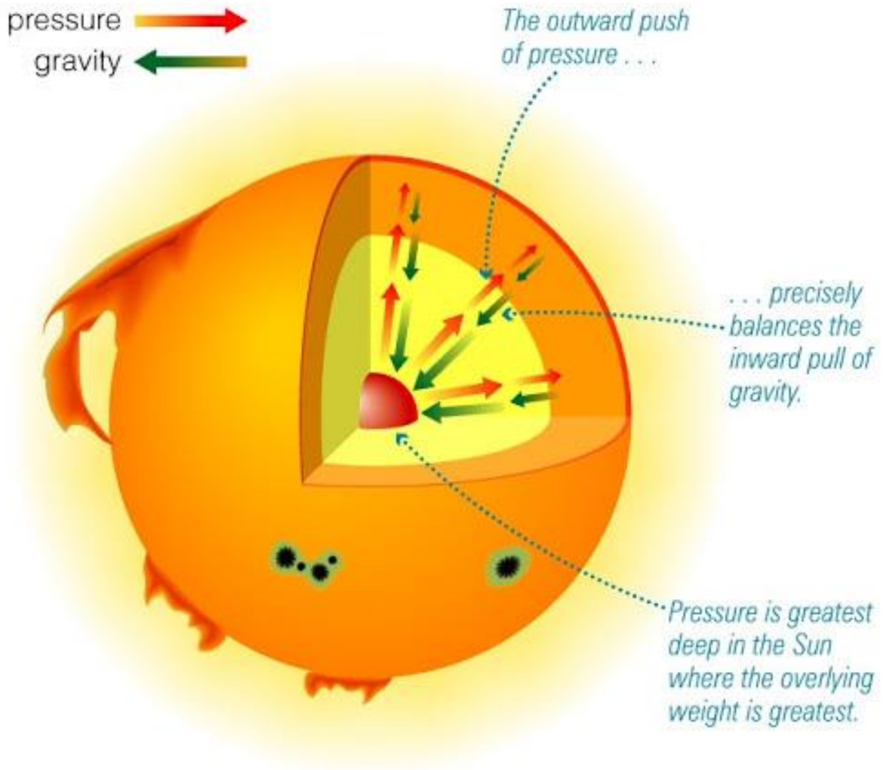
The Sun
today



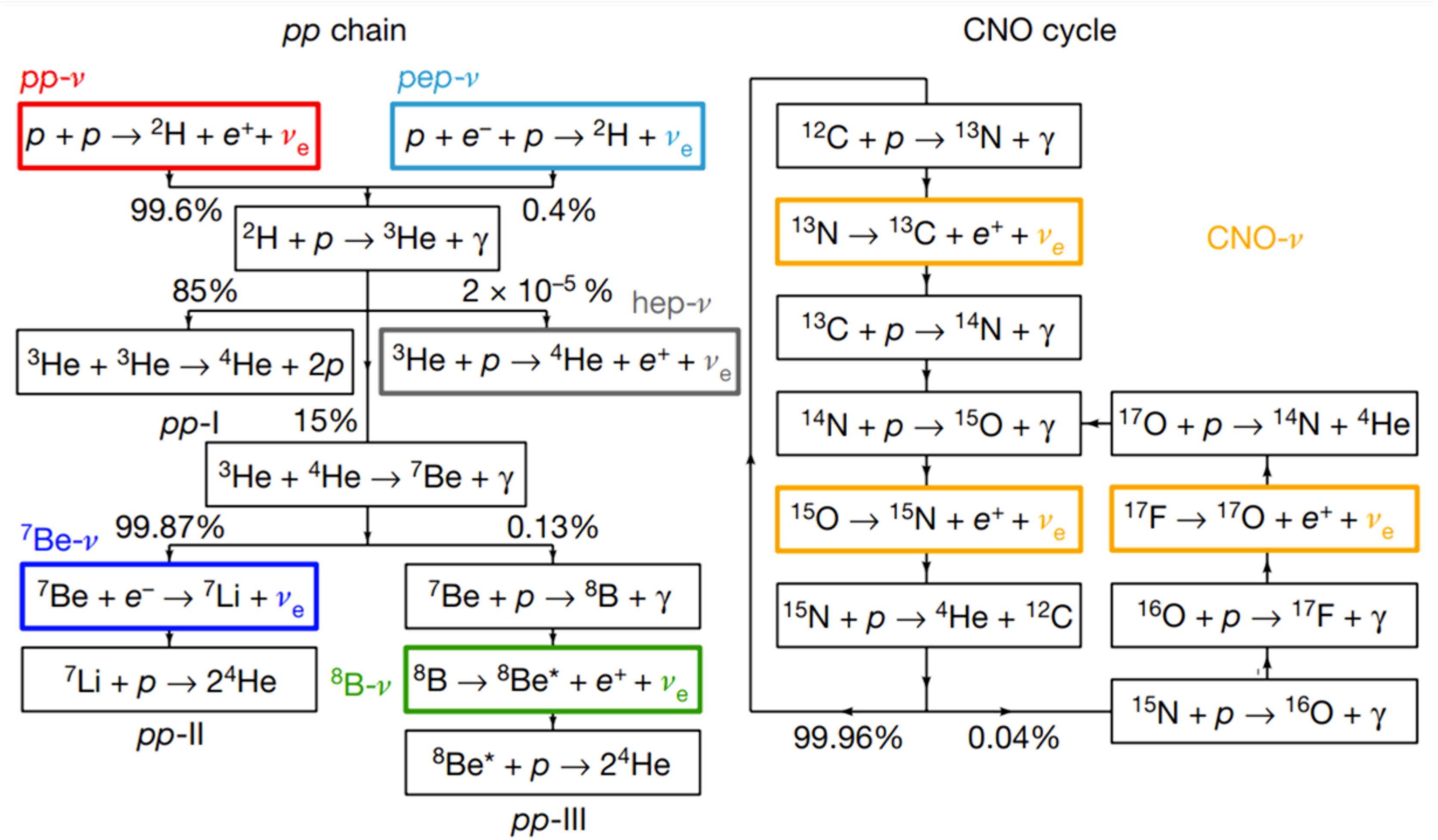


From a molecular cloud to a star...





(Notable examples of H-burning mechanisms)



pp chain

pp-ν

$p + p \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e$

pep-ν

$p + e^{-} + p \rightarrow {}^{2}\mathrm{H} + \nu_e$

99.6%

0.4%

${}^{2}\mathrm{H} + p \rightarrow {}^{3}\mathrm{He} + \gamma$

85%

2×10^{-5} %

hep-ν

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2p$

${}^{3}\mathrm{He} + p \rightarrow {}^{4}\mathrm{He} + e^{+} + \nu_e$

pp-I

15%

${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$

^{7}Be-ν

99.87%

0.13%

${}^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_e$

${}^{7}\mathrm{Be} + p \rightarrow {}^{8}\mathrm{B} + \gamma$

${}^{7}\mathrm{Li} + p \rightarrow 2\,{}^{4}\mathrm{He}$

^{8}B-ν

${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_e$

pp-II

${}^{8}\mathrm{Be}^{*} + p \rightarrow 2\,{}^{4}\mathrm{He}$

pp-III

CNO cycle

${}^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$

${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e$

CNO-ν

${}^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$

${}^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \gamma$

${}^{17}\mathrm{O} + p \rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$

${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e$

${}^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^{+} + \nu_e$

${}^{15}\mathrm{N} + p \rightarrow {}^{4}\mathrm{He} + {}^{12}\mathrm{C}$

${}^{16}\mathrm{O} + p \rightarrow {}^{17}\mathrm{F} + \gamma$

${}^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma$

99.96%

0.04%

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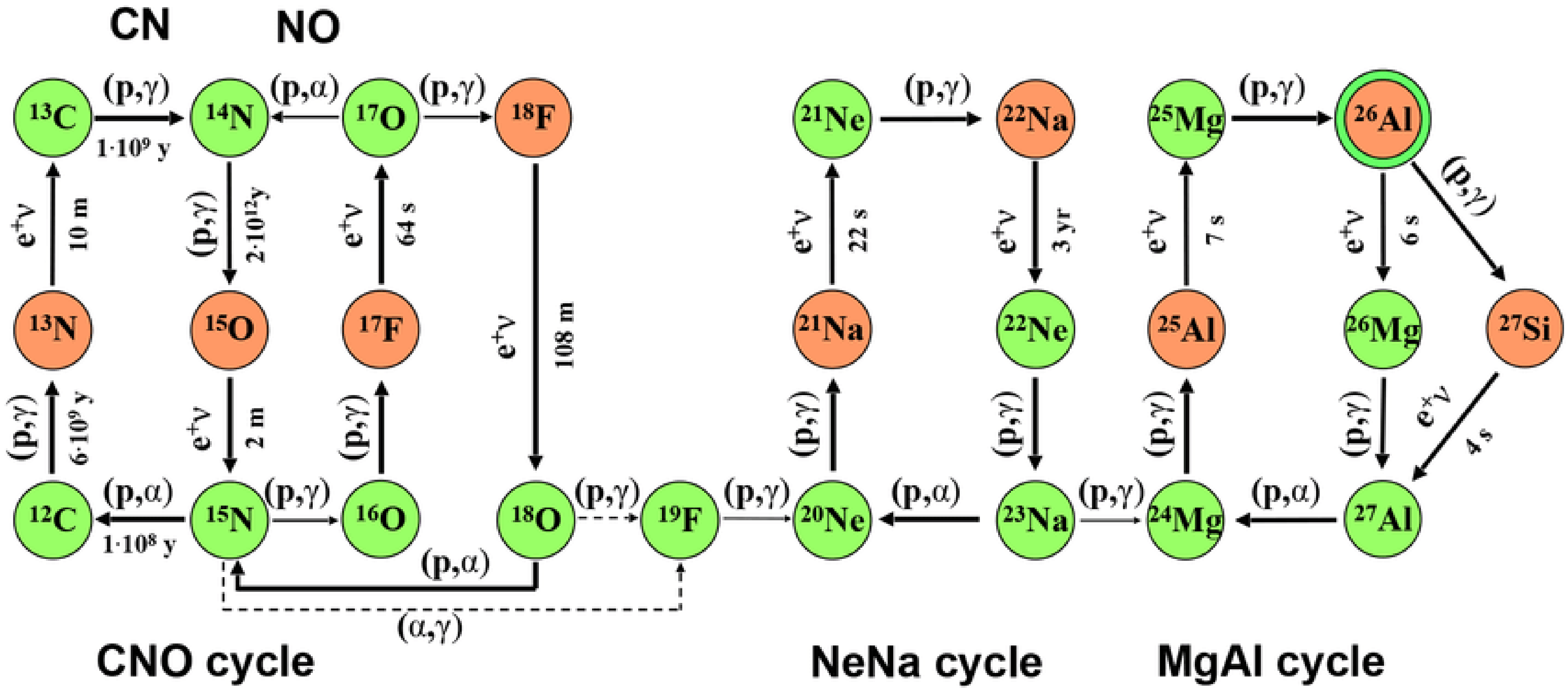
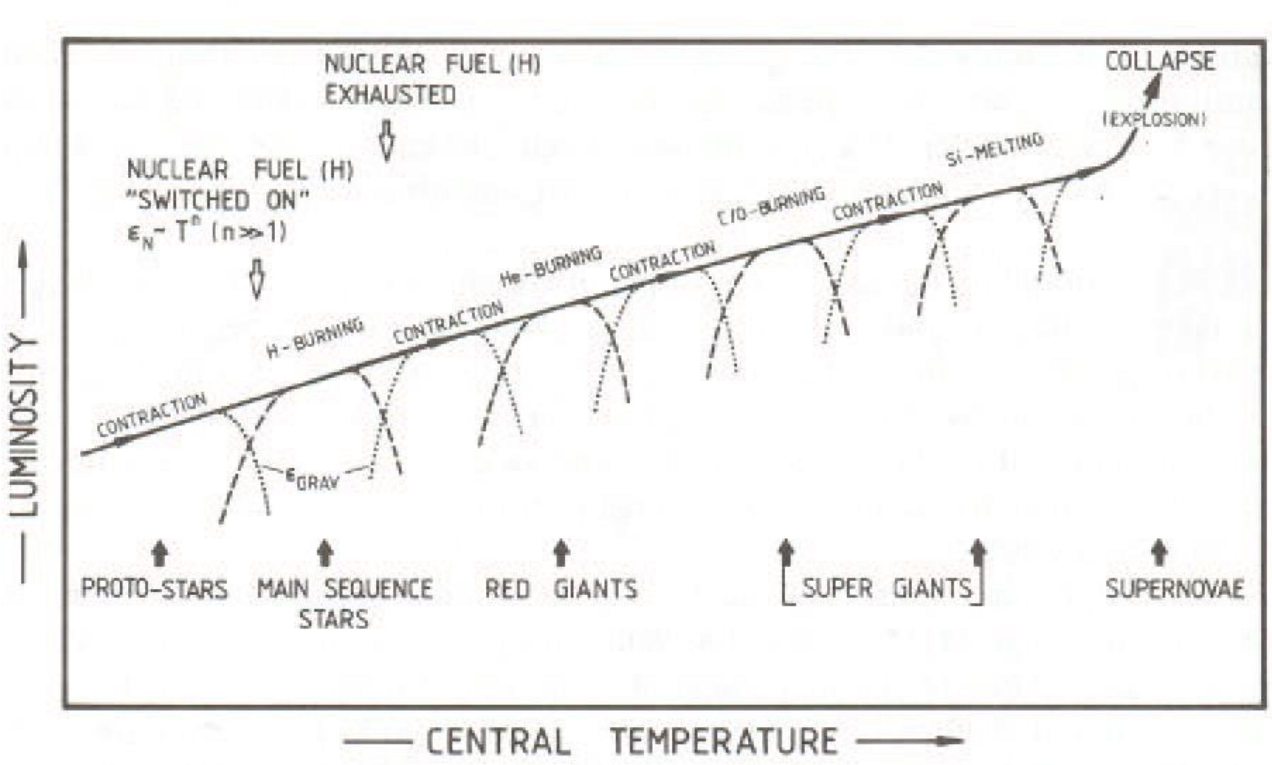
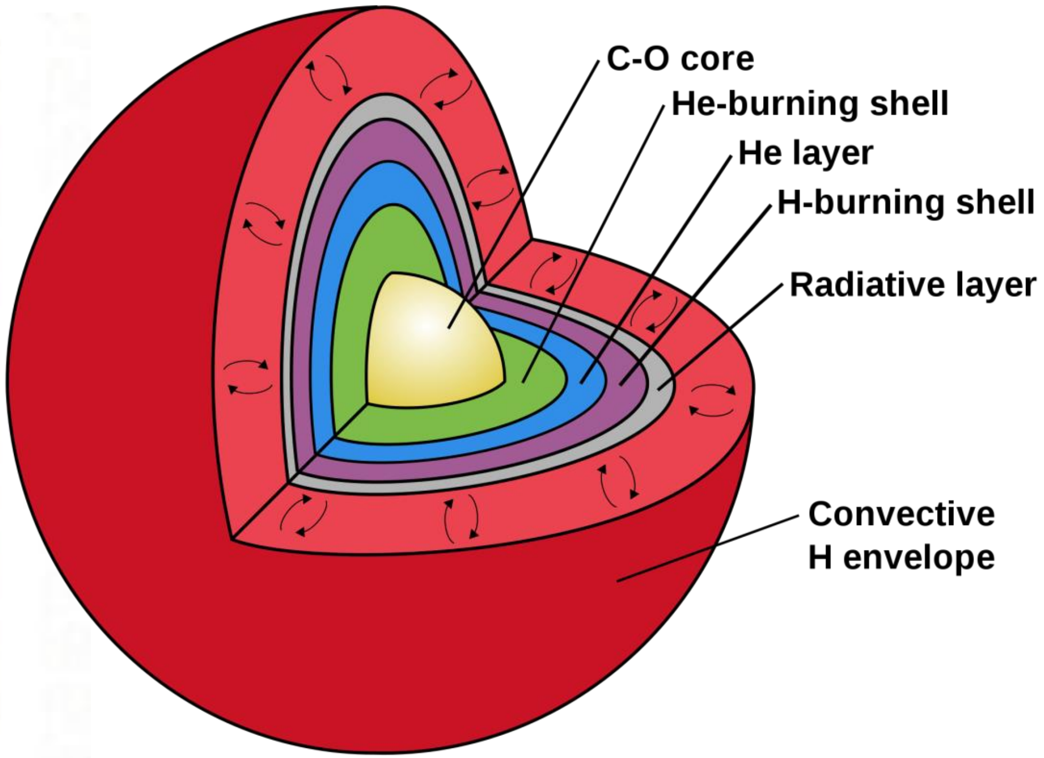
(more advanced H-burning cycles)

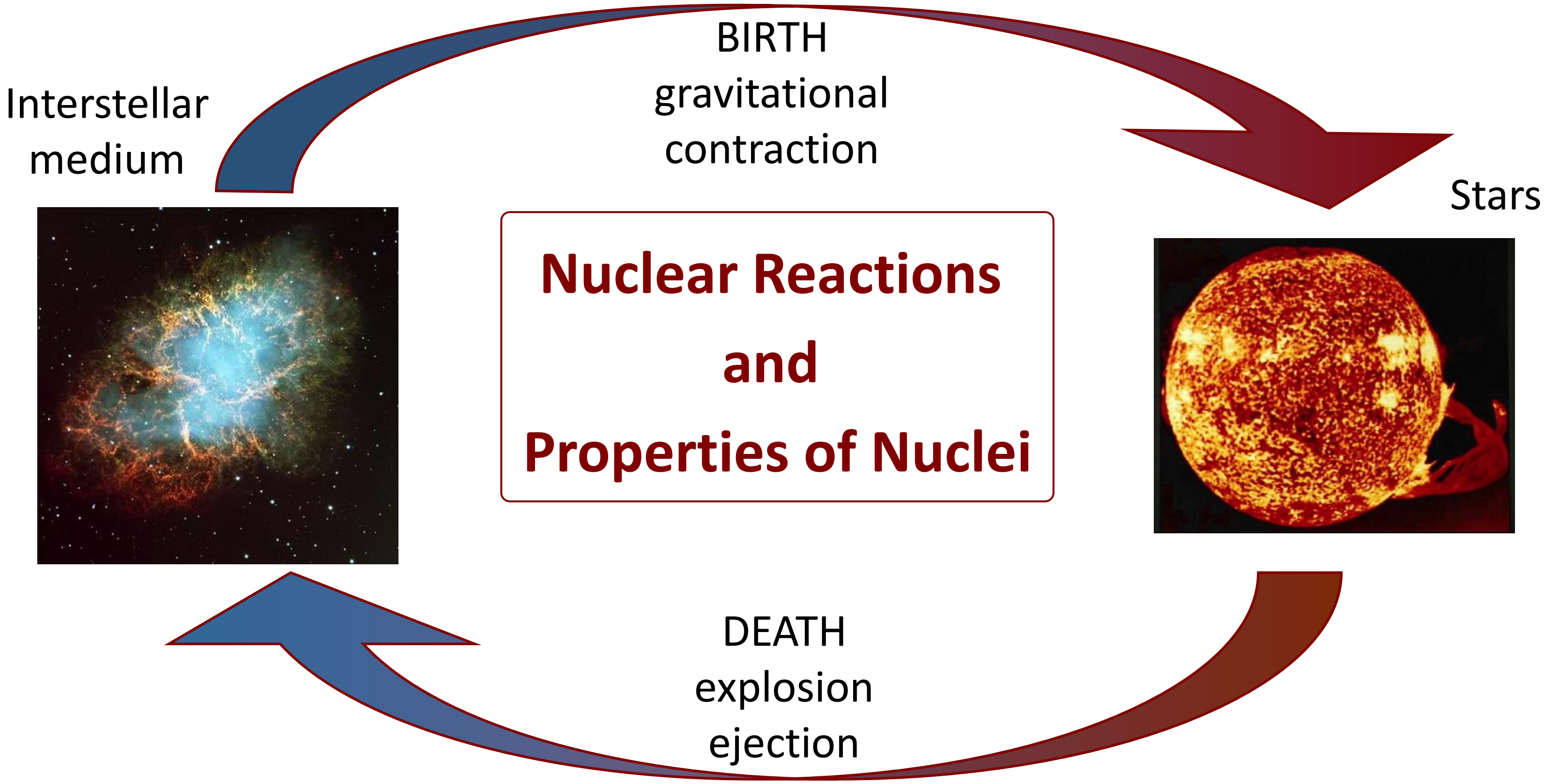


…going through cyclic burning processes…





…to stellar explosions



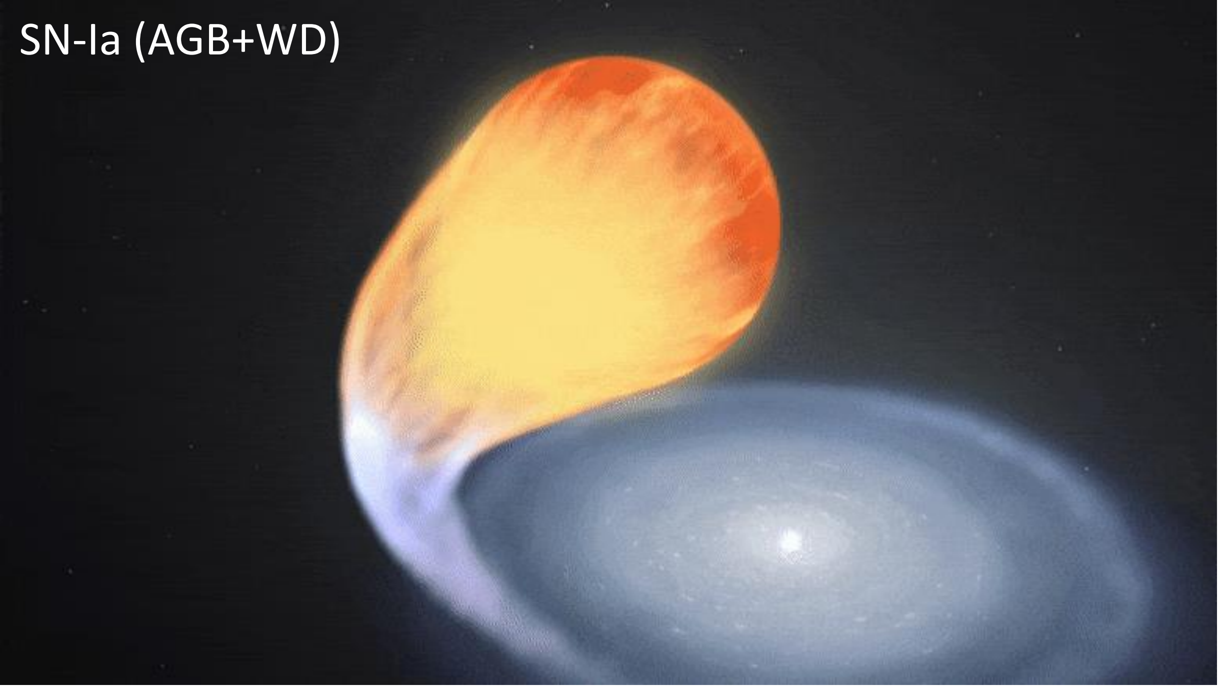
Interstellar medium

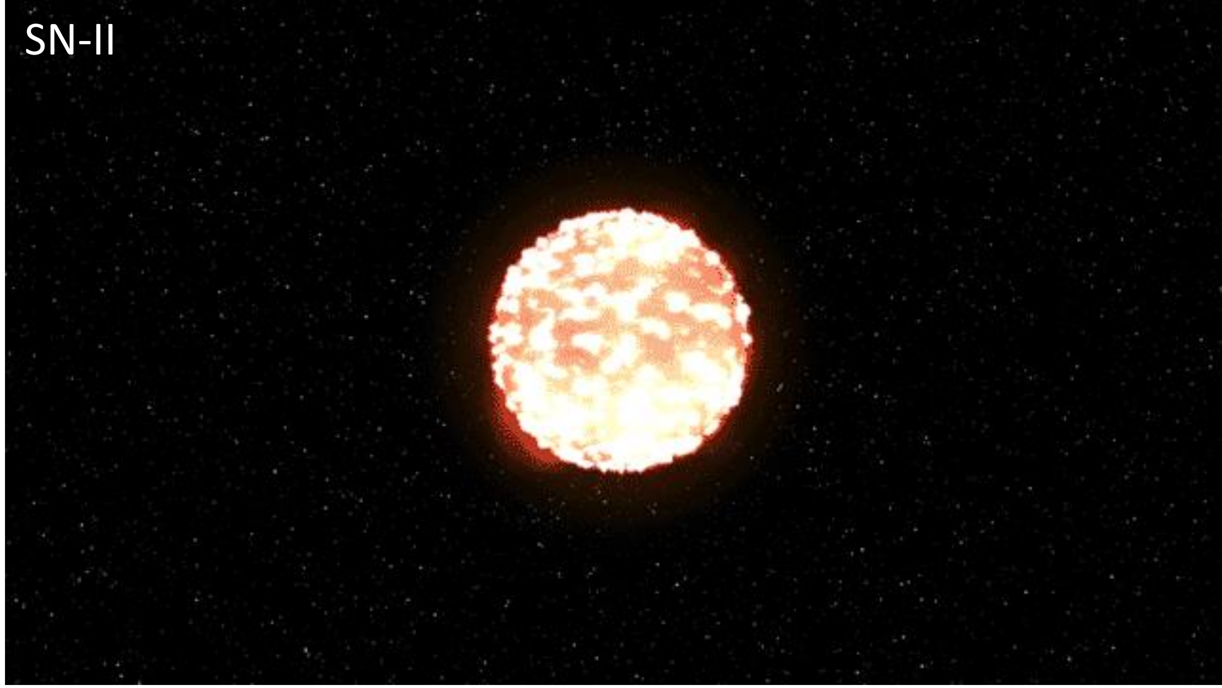
BIRTH
gravitational
contraction

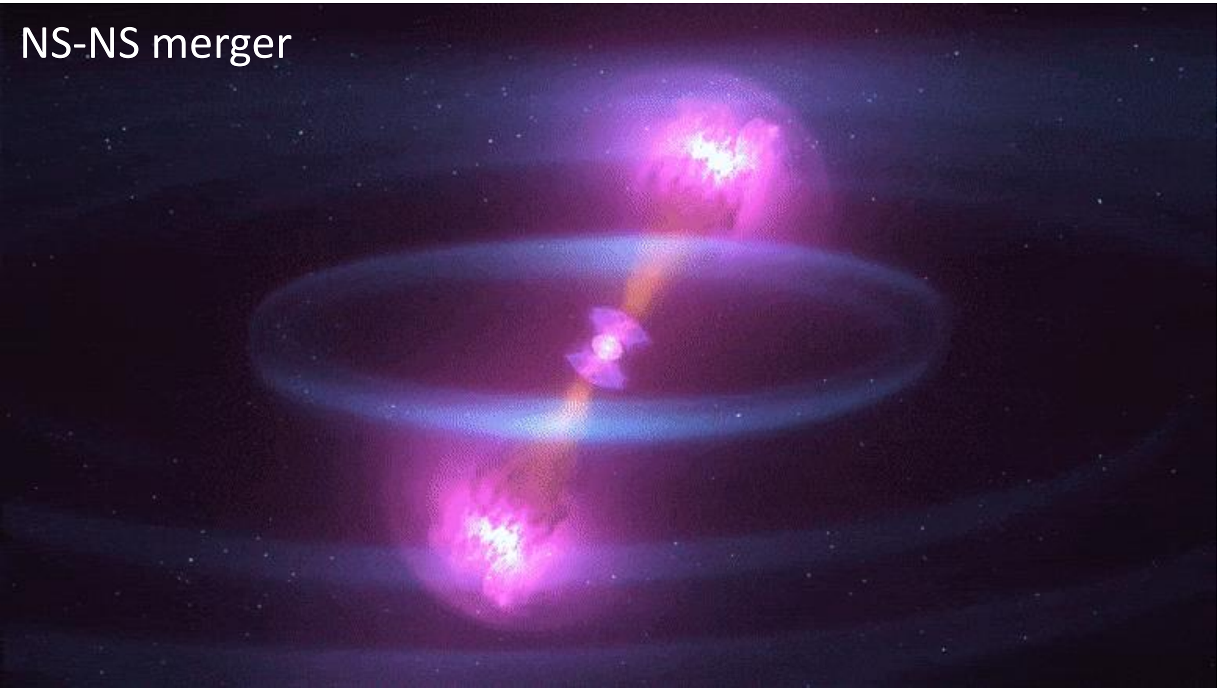
Stars

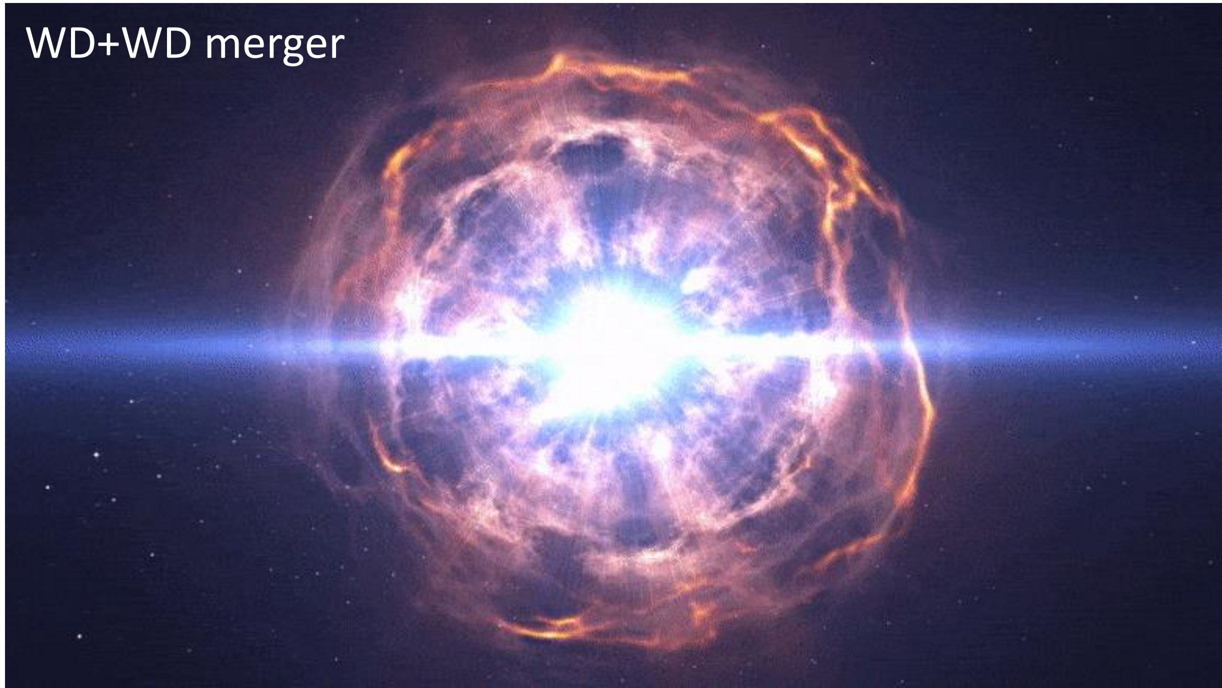
Nuclear Reactions
and
Properties of Nuclei

DEATH
explosion
ejection


SN-Ia (AGB+WD)

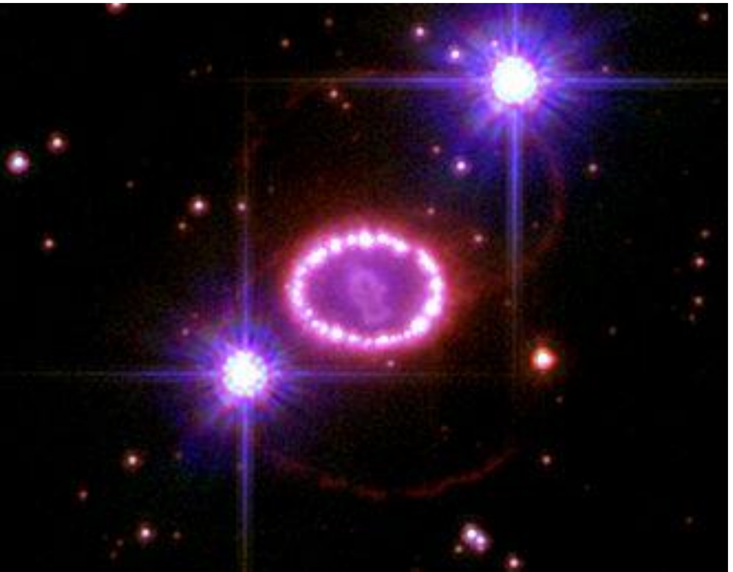

SN-II


NS-NS merger


WD+WD merger

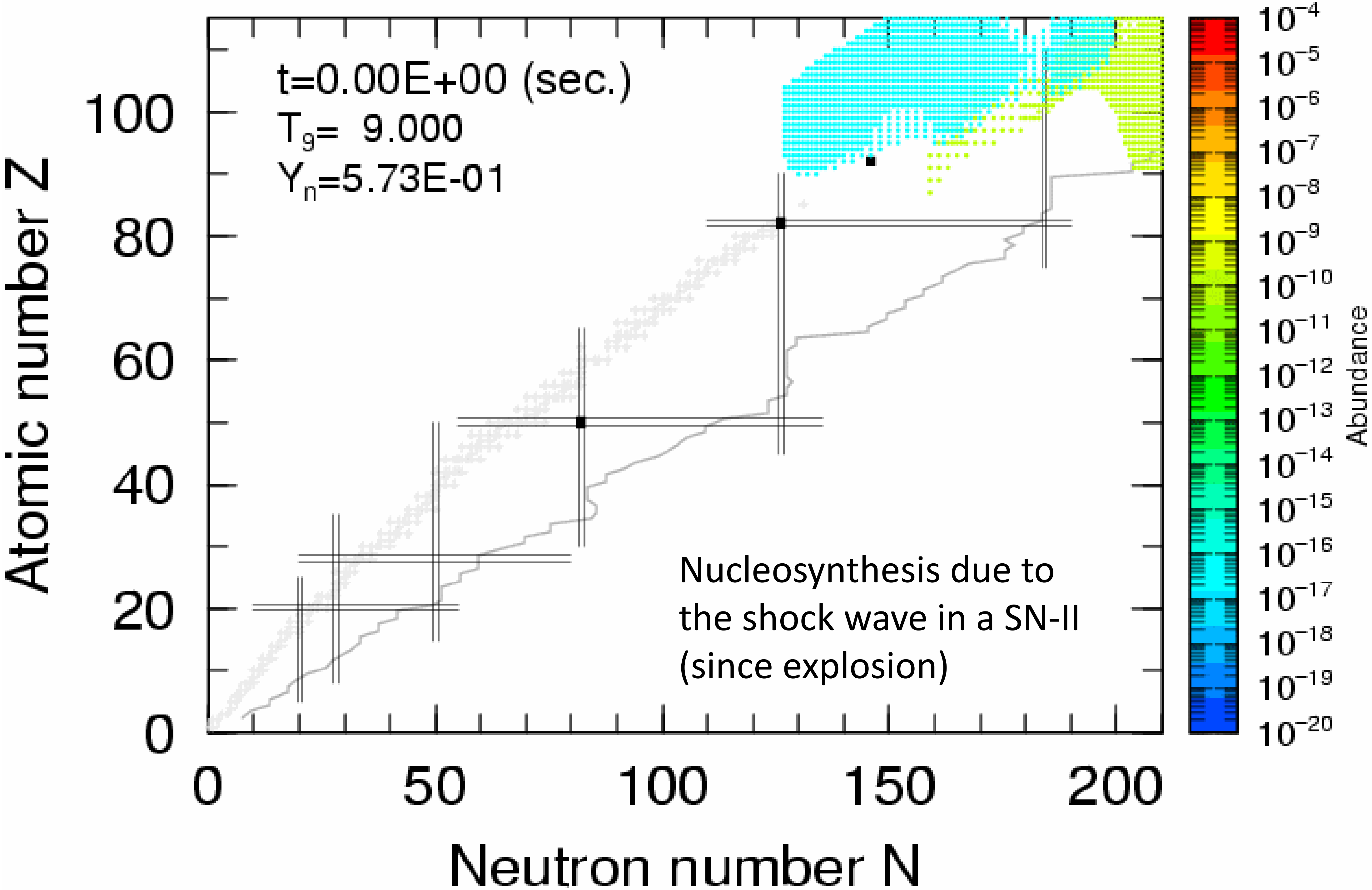
G299.2-02.9,
SNR (Ia) in the Milky Way.
CHANDRA

Crab Nebula,
SNR (II) 1054 in Zeta Tauri.
HST



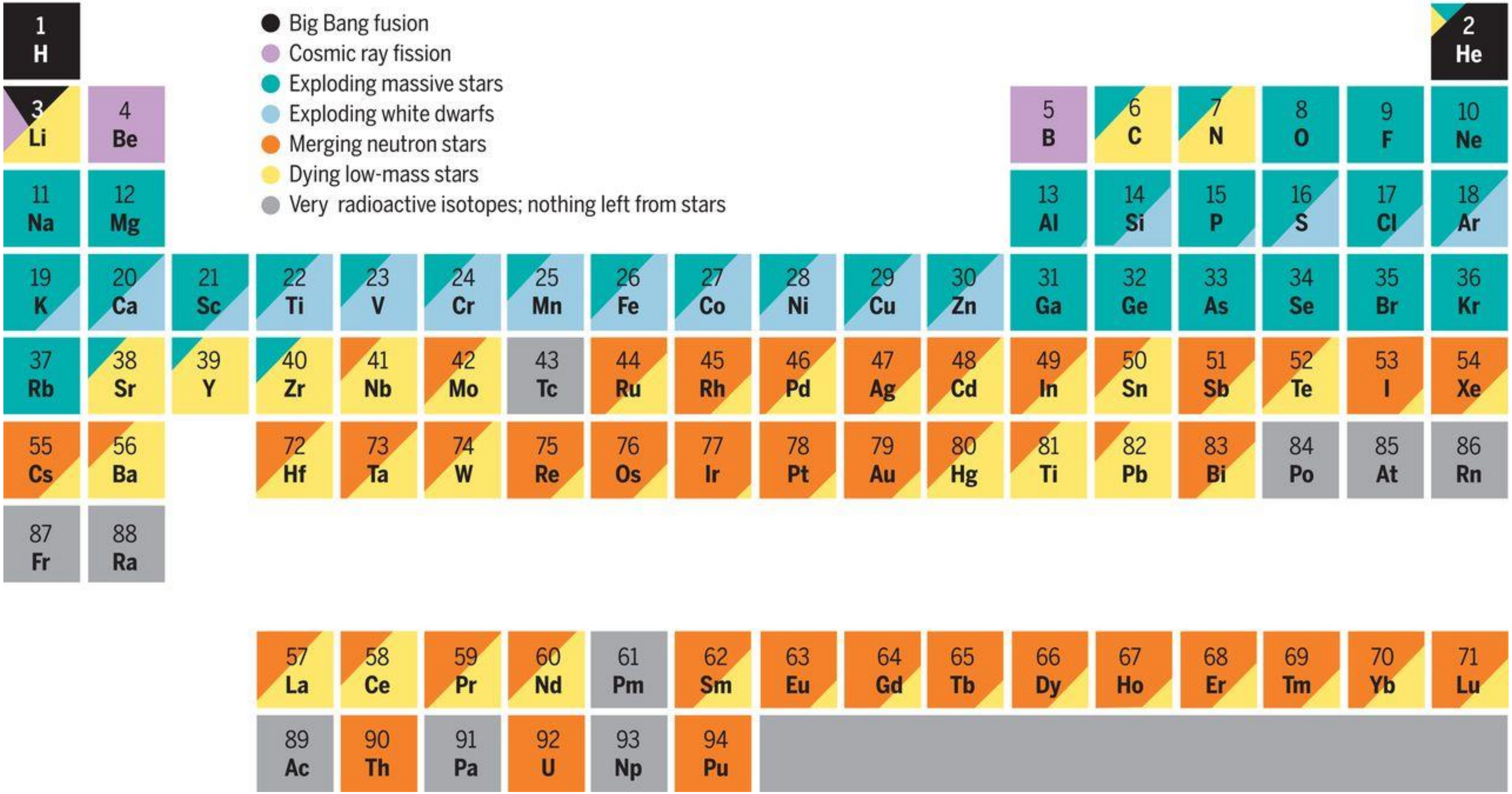
SN 1987A,
SNR (II) in
Big Magellan Cloud.
HST

“Pillars of creation” in NGC 3324, Carina Nebula.
JWST



Nucleosynthesis due to the shock wave in a SN-II (since explosion)

The evolving composition of the Universe



Jennifer A. Johnson, Populating the periodic table: Nucleosynthesis of the elements.*Science***363**, 474-478(2019).DOI:10.1126/science.aau9540

How do nuclear reactions take place?

The energy of nuclei in a plasma follows a **Maxwell-Boltzmann distribution**

the **cross section** falls faster than exponentially as the energy decreases

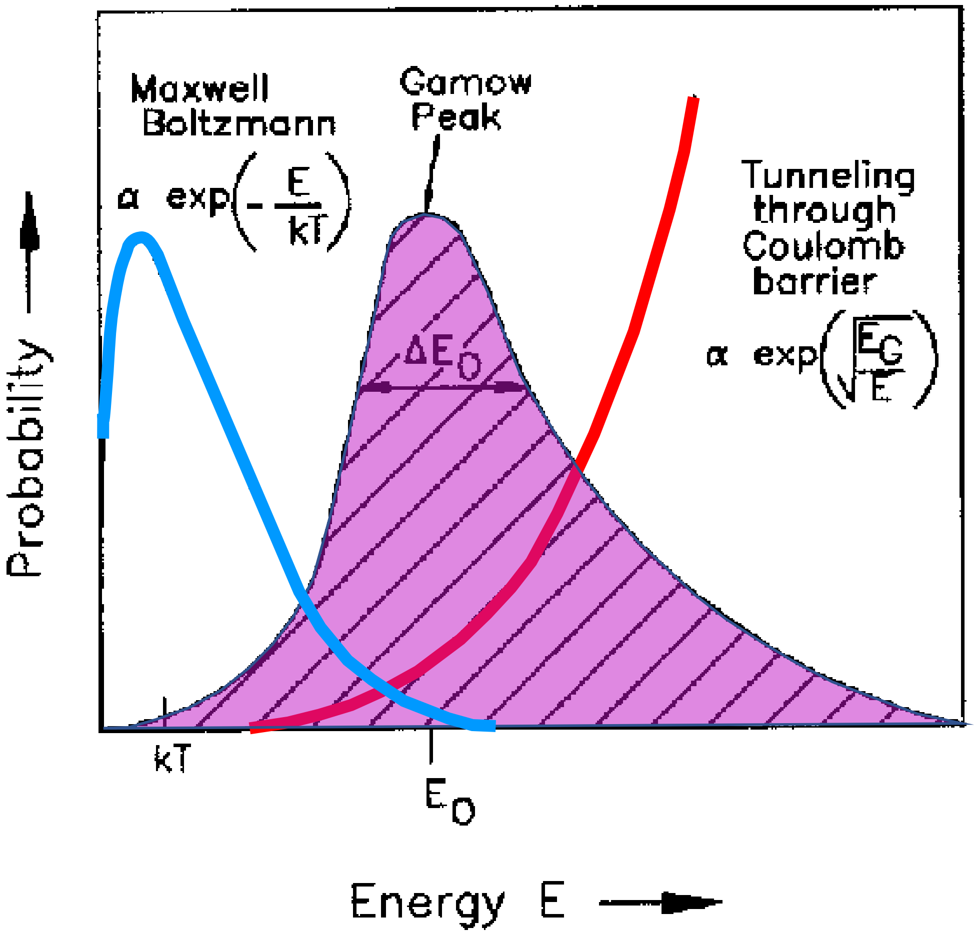
Consider a reaction

$$A + B \rightarrow C + D$$

The **reaction rate** (input of evolutionary **models**) is given by

$$\langle r \rangle = \mathrm{N_A N_B} \int_0^\infty \phi(v)\, \sigma(v)\, v\, \mathrm{d}v$$

The **Gamow peak** defines the relevant energy range for this reaction to occur



Challenges of Nuclear Astrophysics

Below a certain energy, the experimental counting rate is too low and the cosmic-ray induced background prevents the direct measurement of the cross section

$\mathbf{\mathit{experimental\ counting\ rate}}$	
$=$	
$beam\ flux$	10^{14} pps (100 μA 1^{+} beam)
$\times$	
$target\ nuclei\ areal\ density$	10^{19} atoms/cm^{2} (often smaller)
$\times$	
$cross\ section$	10^{-36} cm^{2} (often smaller)
$\times$	
$detection\ efficiency$	10^{-1} (often smaller)
	a few counts/day

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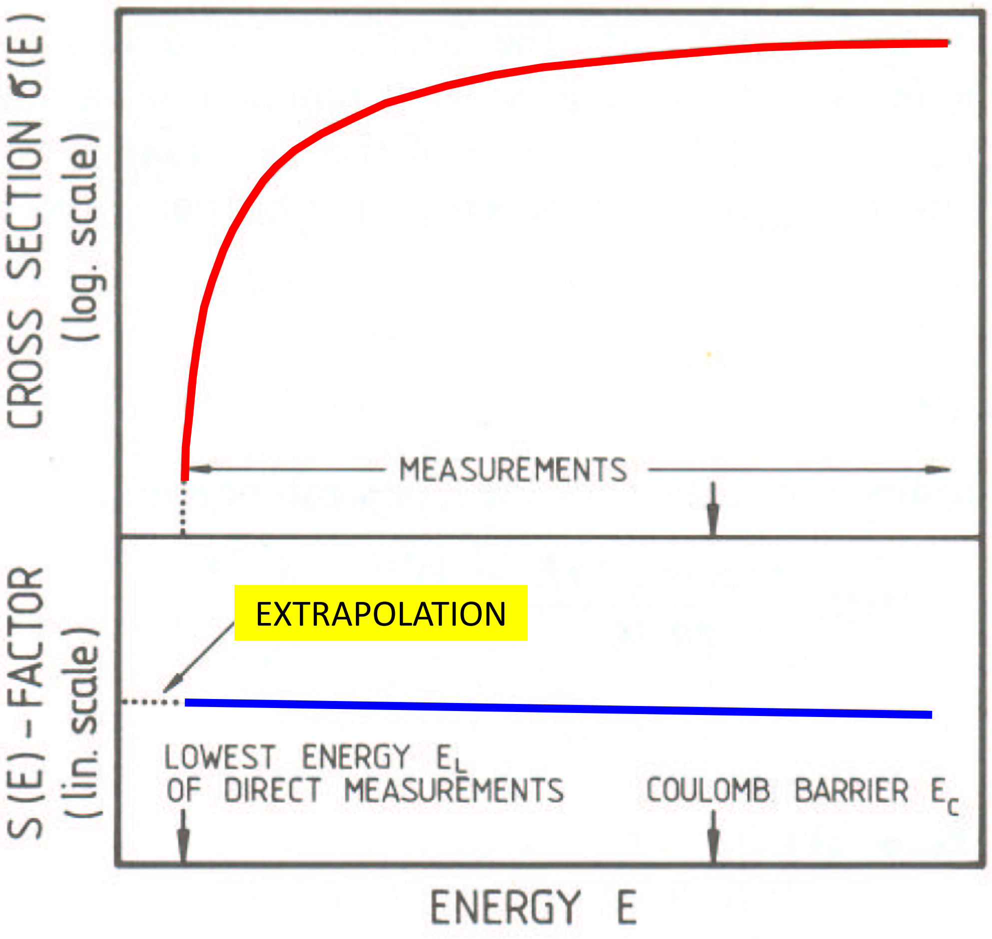
Challenges of Nuclear Astrophysics

Below a certain energy, the experimental counting rate is too low and the cosmic-ray induced background prevents the direct measurement of the cross section

Introducing the **astrophysical S-factor S(E)** and factorizing the **Coulomb interaction term** apart:

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

it is possible to measure the cross section at high energy and extrapolate the astrophysical factor *S(E)* in the interesting energy range (Gamow window)



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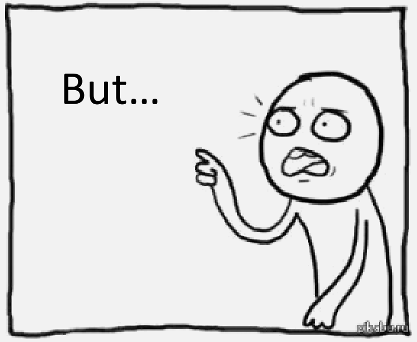
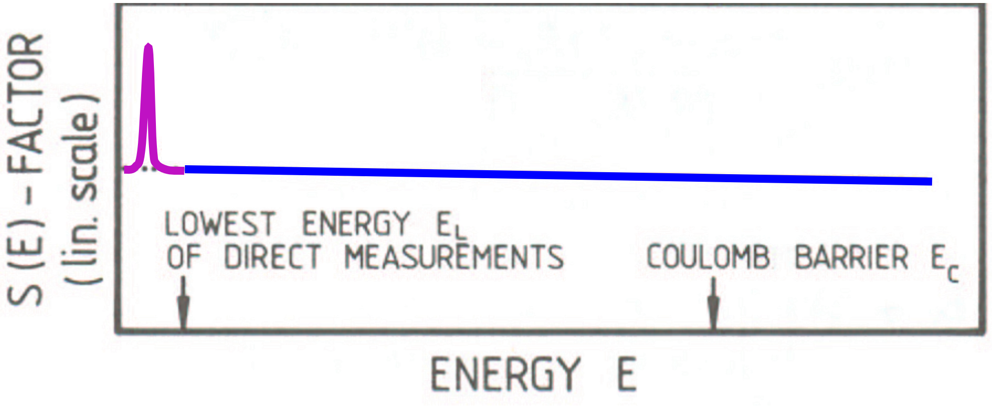


unexpected low-energy resonances may be present in the extrapolation region!



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Methods to takle these challenges

- **Indirect measurements**
  - THM
  - ANC
  - Coulomb dissociation
- **Underground Direct measurements**

The cross section of a **suitable two-body to three-body reaction** (A+x → c+B+y) is **used to extract the cross section for a relevant two-body reaction** (A + a → c + B) at stellar energies.

Based on the normalization of the tail of the quantum overlap **of bound state wave functions** of the initial and final nuclei

As Coulomb induced dissociation is an inverse to the radiative capture process, one can **relate the measured Coulomb dissociation cross section** (which can be measured at high beam energies and are larger in magnitude) **to the relevant radiative capture cross section**

Methods to takle these challenges

- **Indirect measurements**
  - THM
  - ANC
  - Coulomb dissociation

Model dependent,
Need normalization

- **Underground Direct measurements**

Model independent
Need no normalization

Methods to takle these challenges

- **Indirect measurements**
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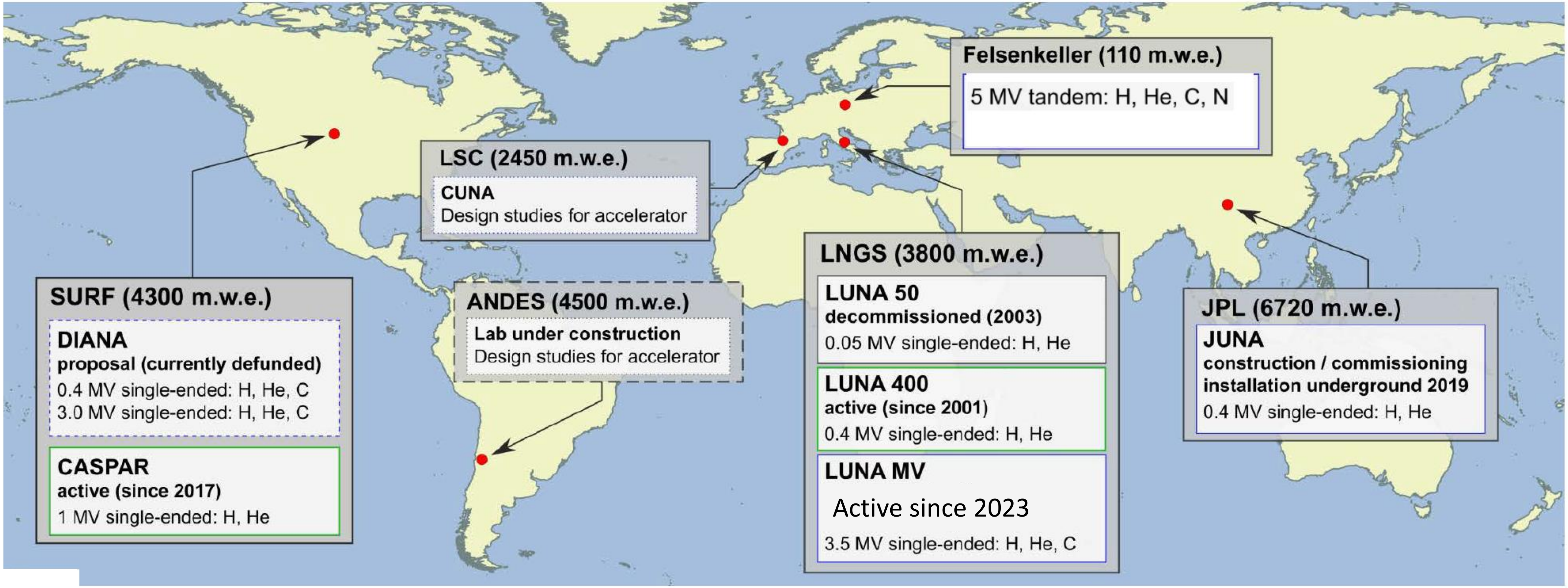
Model dependent,
Need normalization

- **Underground Direct measurements**

Model independent
Need no normalization

Nuclear Astrophysics Underground Laboratories



Felsenkeller (110 m.w.e.)

5 MV tandem: H, He, C, N

LSC (2450 m.w.e.)

CUNA
Design studies for accelerator

SURF (4300 m.w.e.)

DIANA
proposal (currently defunded)
0.4 MV single-ended: H, He, C
3.0 MV single-ended: H, He, C

CASPAR
active (since 2017)
1 MV single-ended: H, He

ANDES (4500 m.w.e.)

Lab under construction
Design studies for accelerator

LNGS (3800 m.w.e.)

LUNA 50
decommissioned (2003)
0.05 MV single-ended: H, He

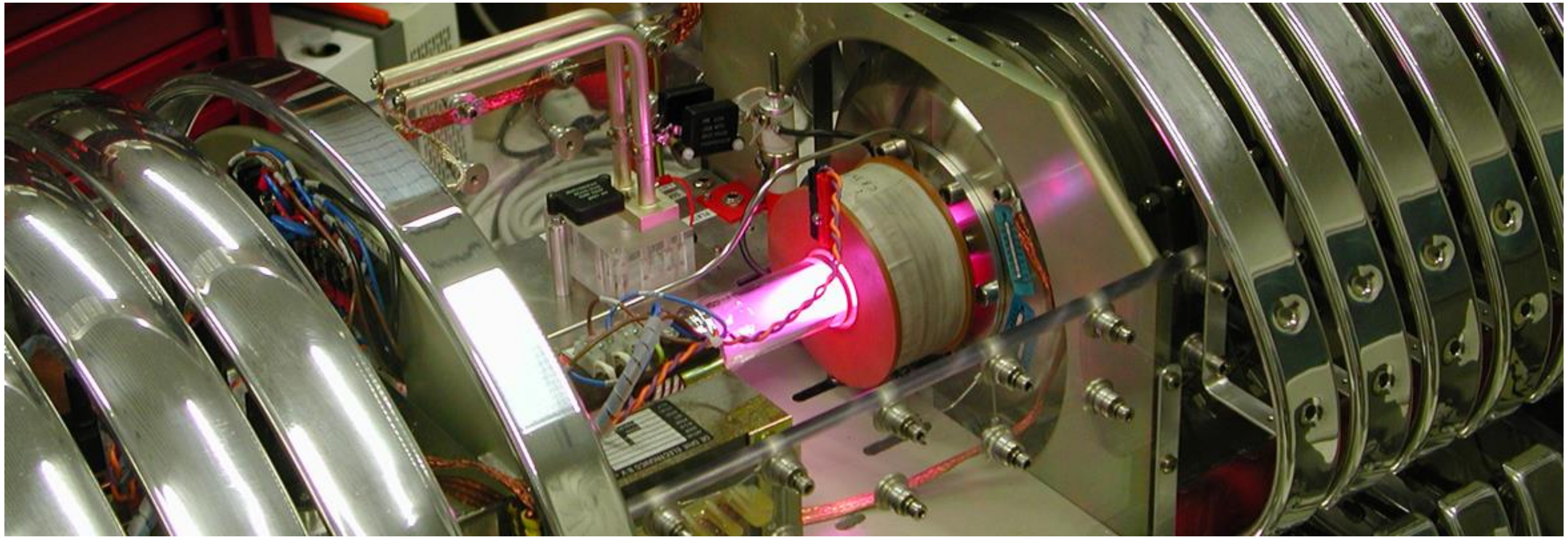
LUNA 400
active (since 2001)
0.4 MV single-ended: H, He

LUNA MV
Active since 2023
3.5 MV single-ended: H, He, C

JPL (6720 m.w.e.)

JUNA
construction / commissioning
installation underground 2019
0.4 MV single-ended: H, He

LUNA
Laboratory for Underground
Nuclear Astrophysics



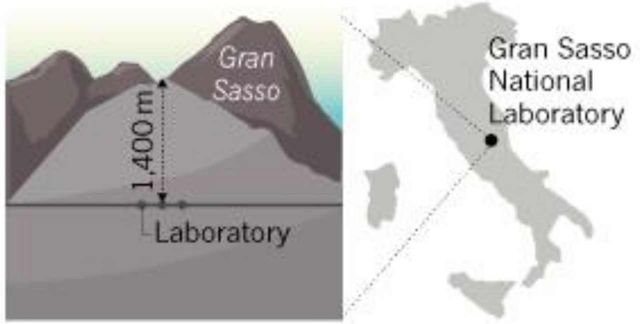
It has been the only underground accelerator for nuclear astrophysics for 25 years

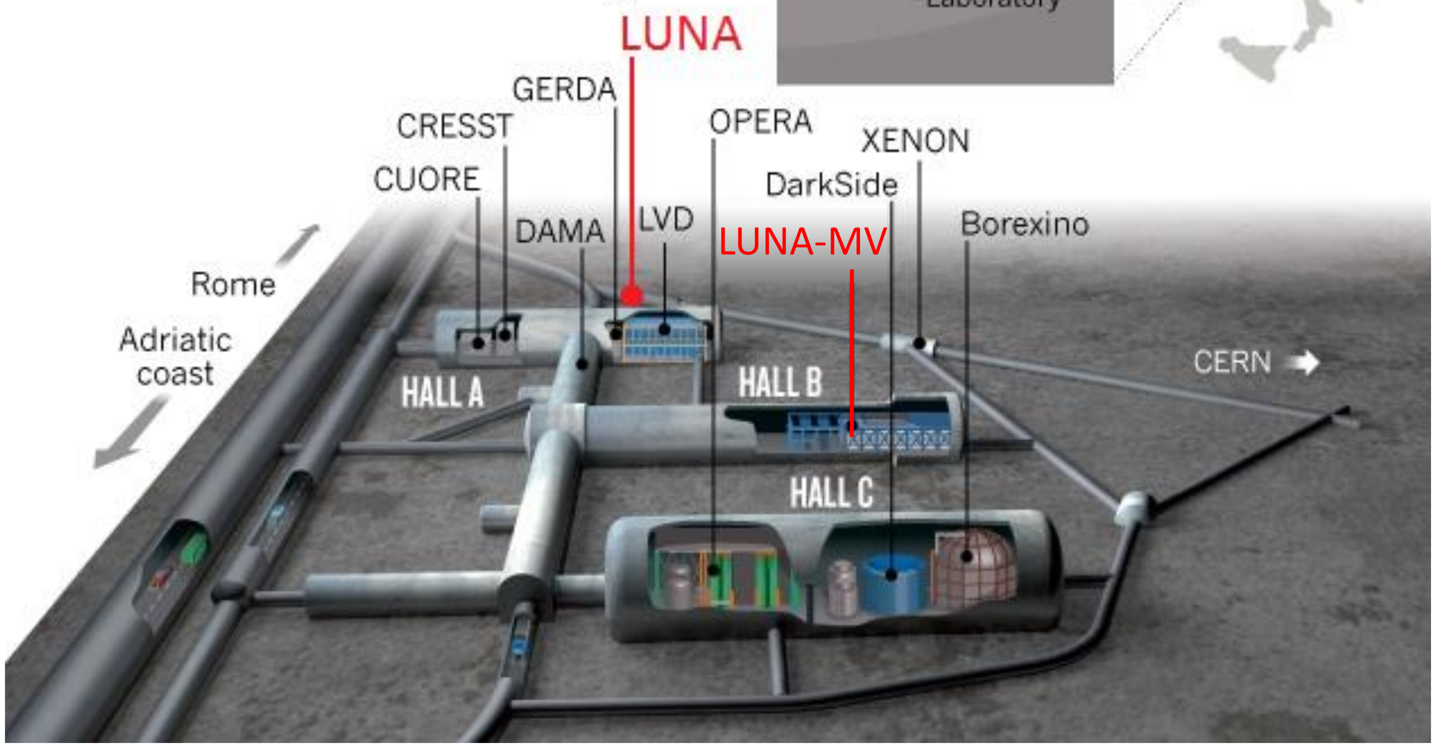
Its results include

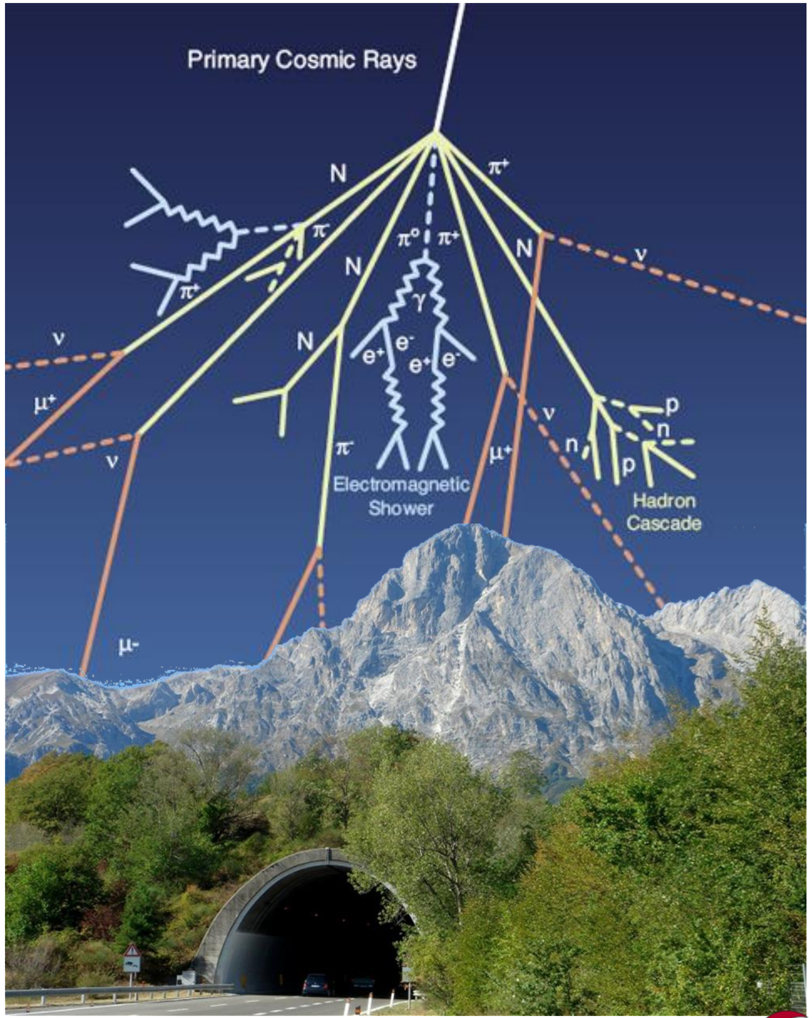
- solar physics (solar neutrinos)
- cosmological model
- big bang nucleosynthesis (BBN)
- stellar nucleosynthesis

The Gran Sasso National Laboratory (LNGS)

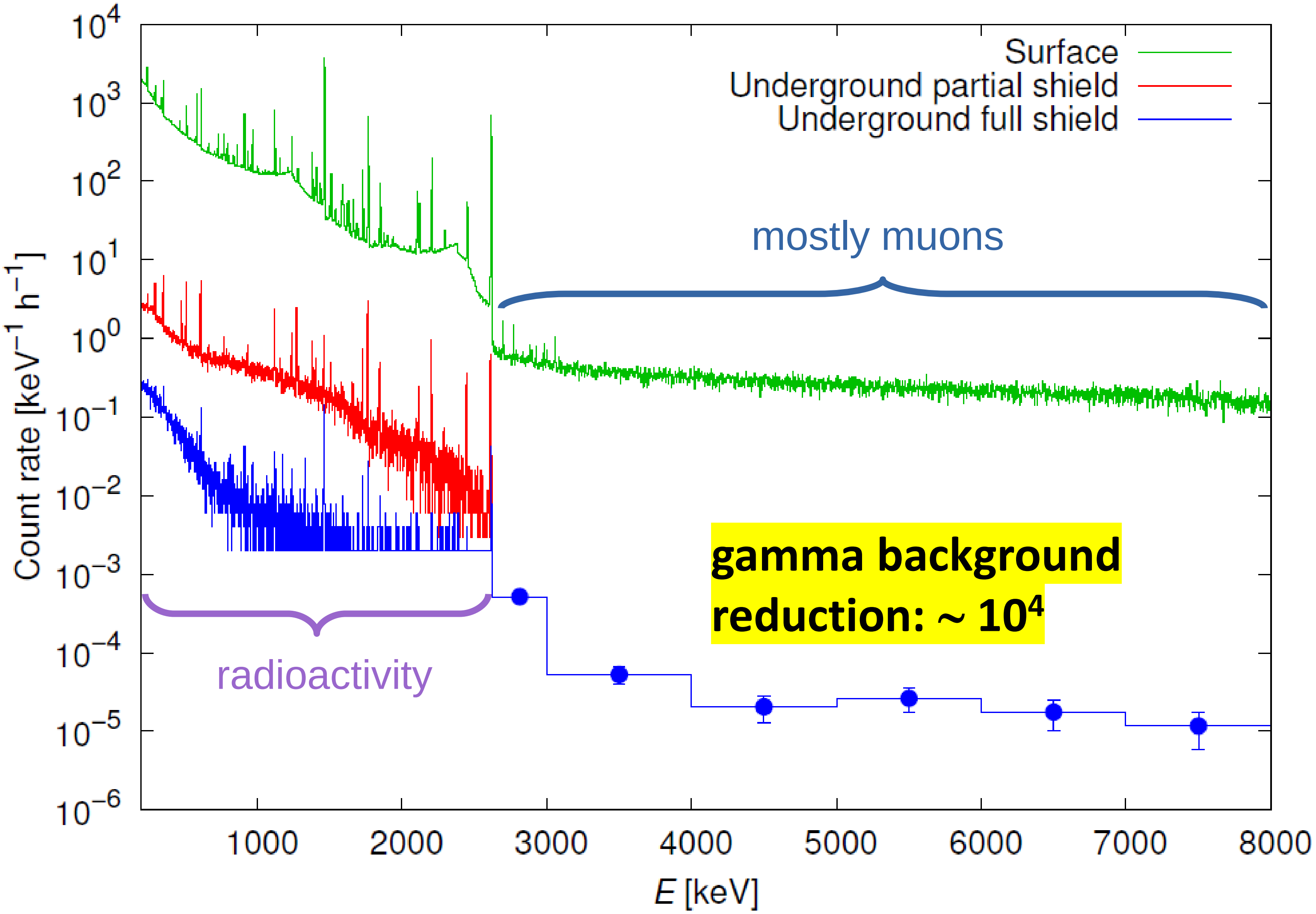
Min. overburden: 3400 mwe
muon flux reduction: $\sim 10^6$
neutron flux reduction: $\sim 10^3$







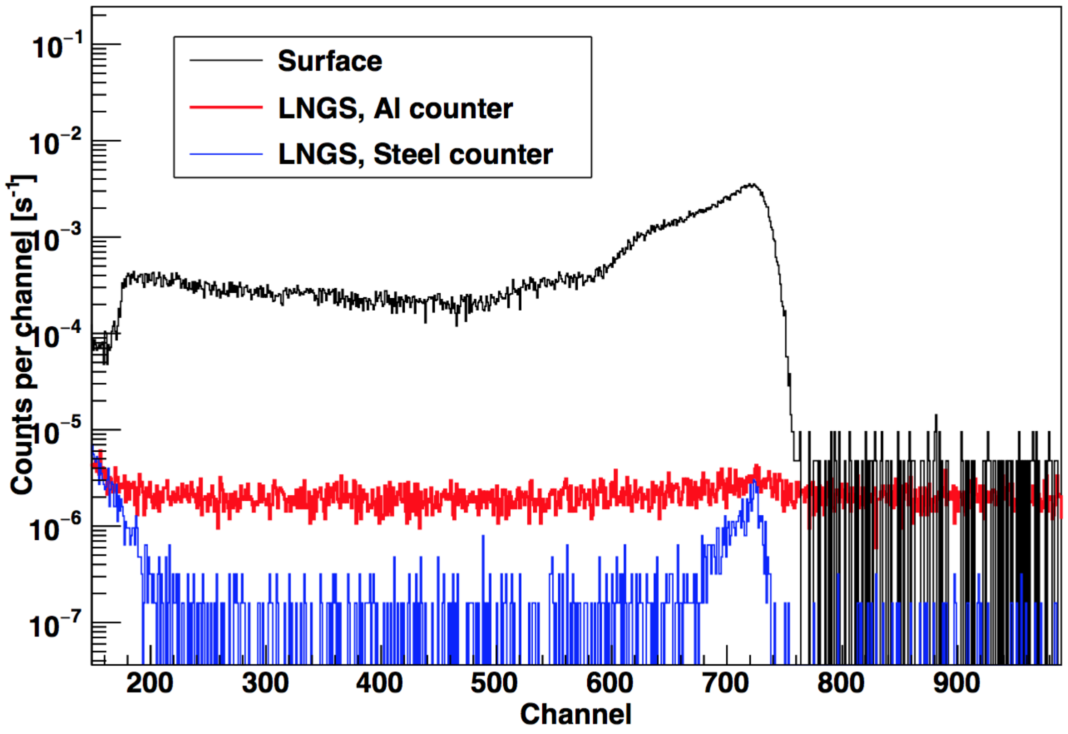
Gamma background reduction



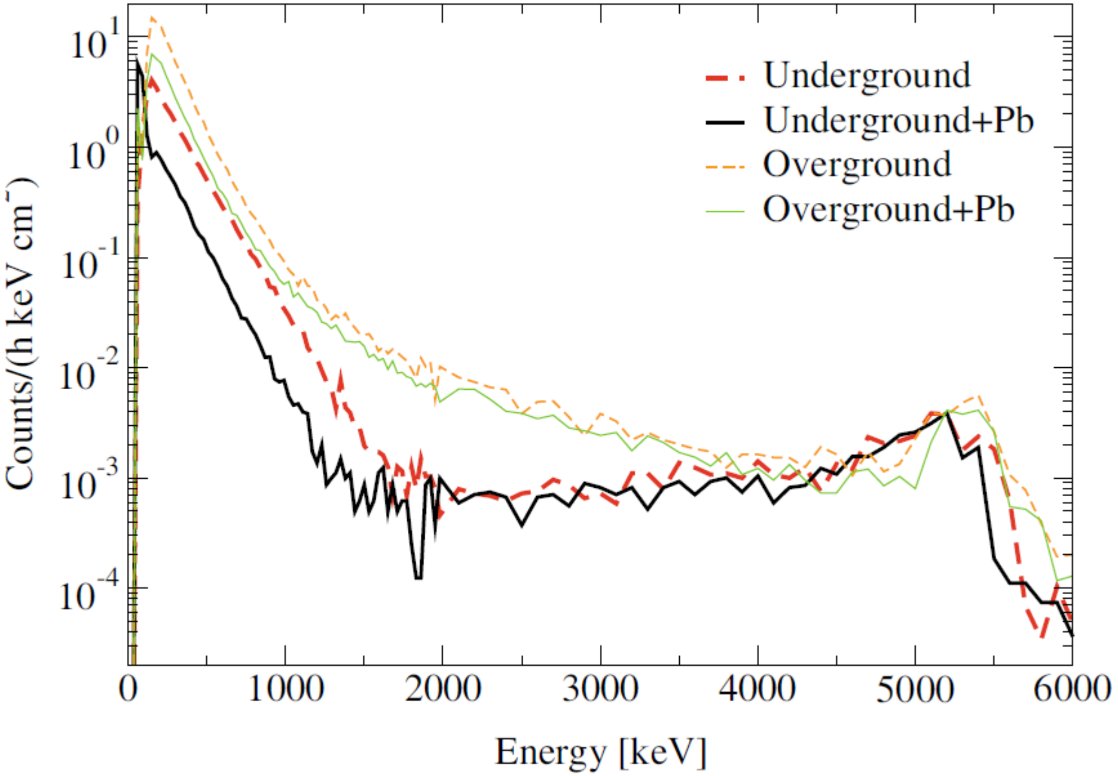
gamma background reduction: ~ 10^4

Reduction of particle background

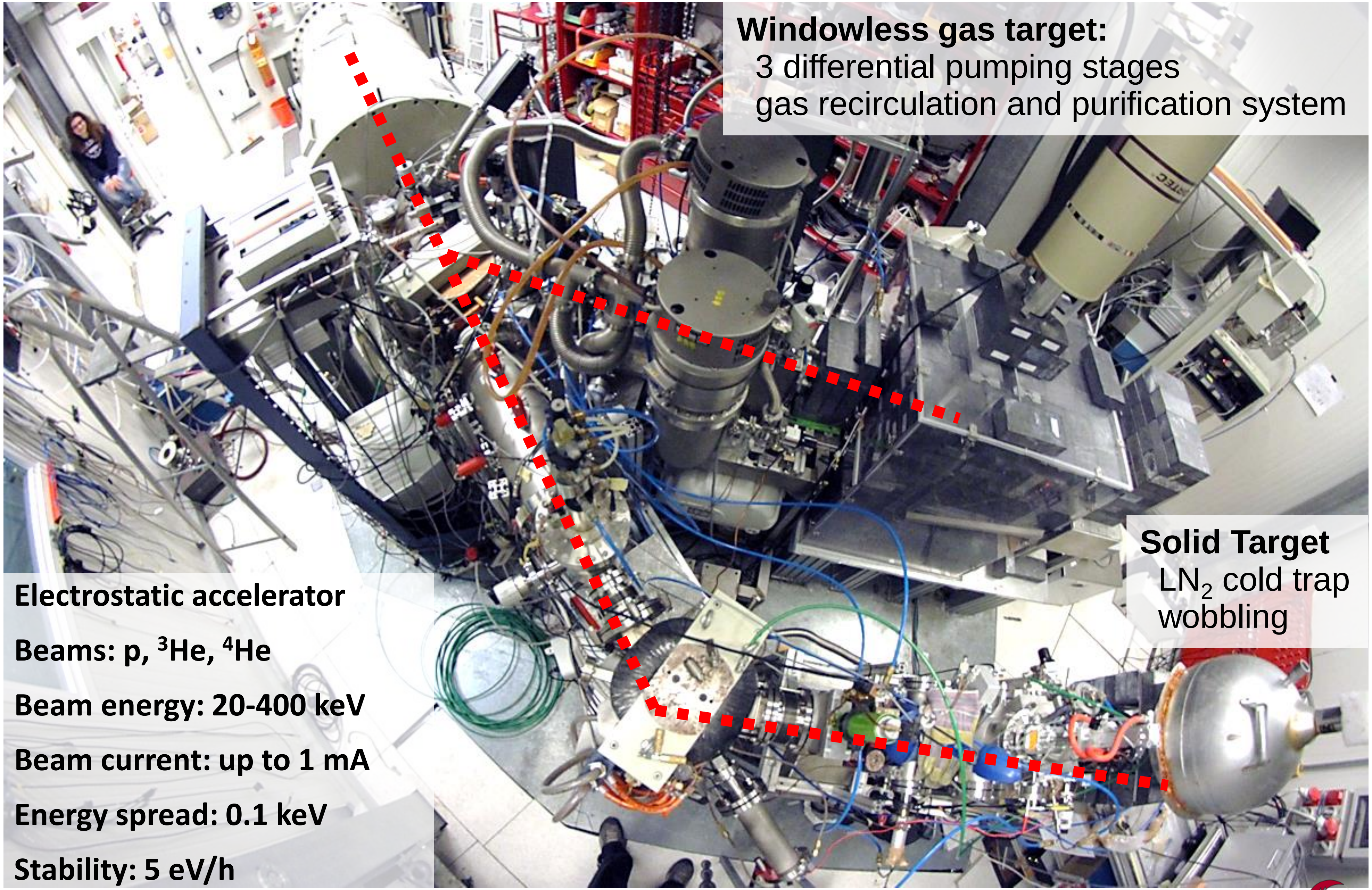
Neutrons



Charged particles



LUNA 400 kV
(2001-today)



Windowless gas target:
3 differential pumping stages
gas recirculation and purification system

Solid Target
LN_2 cold trap
wobbling

Electrostatic accelerator

Beams: p, ^{3}He, ^{4}He

Beam energy: 20-400 keV

Beam current: up to 1 mA

Energy spread: 0.1 keV

Stability: 5 eV/h

One recent measurement: $D(p,\gamma)^3He$

It was the most uncertain nuclear physics input to BBN calculations

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Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino ✉, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli ✉ -Show fewer authors

Nature **587**, 210–213 (2020) | Cite this article

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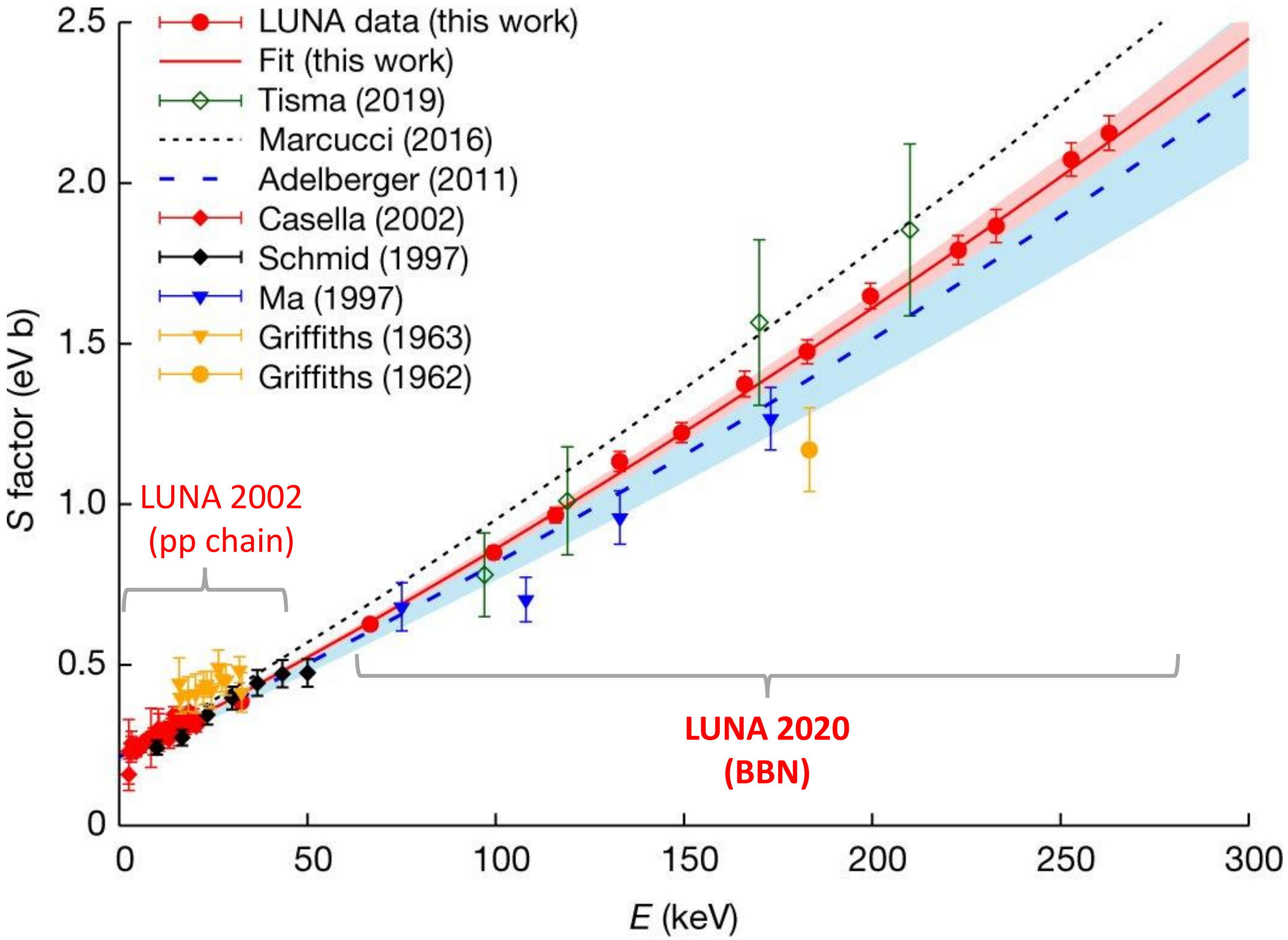
Our measurement improved the reliability in the use of primordial abundances as probes of the physics of the early Universe

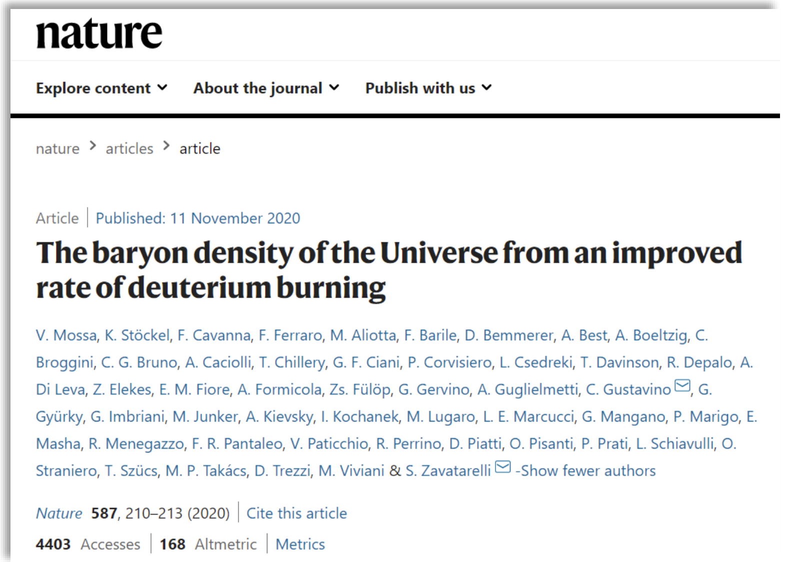


LUNA 2002
(pp chain)

LUNA 2020
(BBN)

One recent measurement: $D(p,\gamma)^3He$

It was the most uncertain nuclear physics input to BBN calculations



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Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

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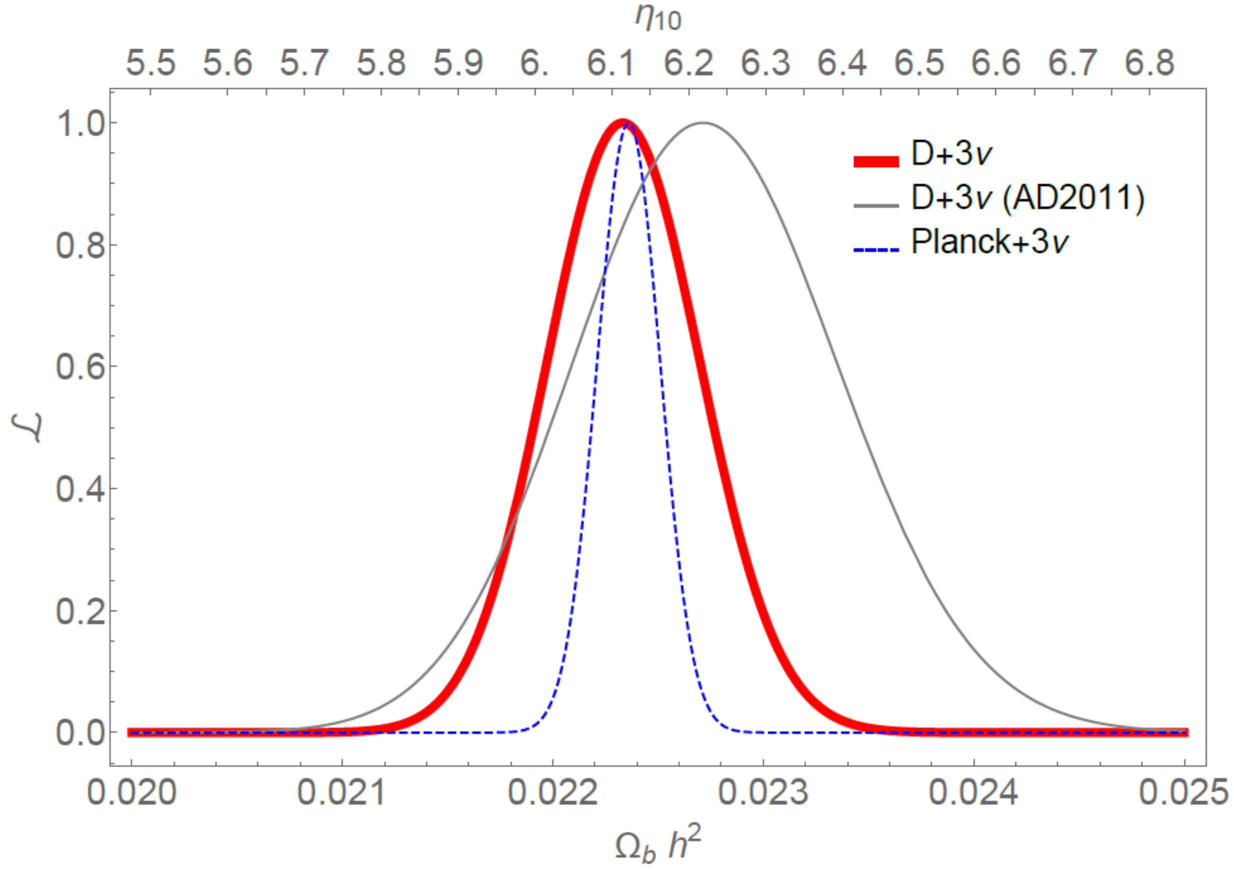
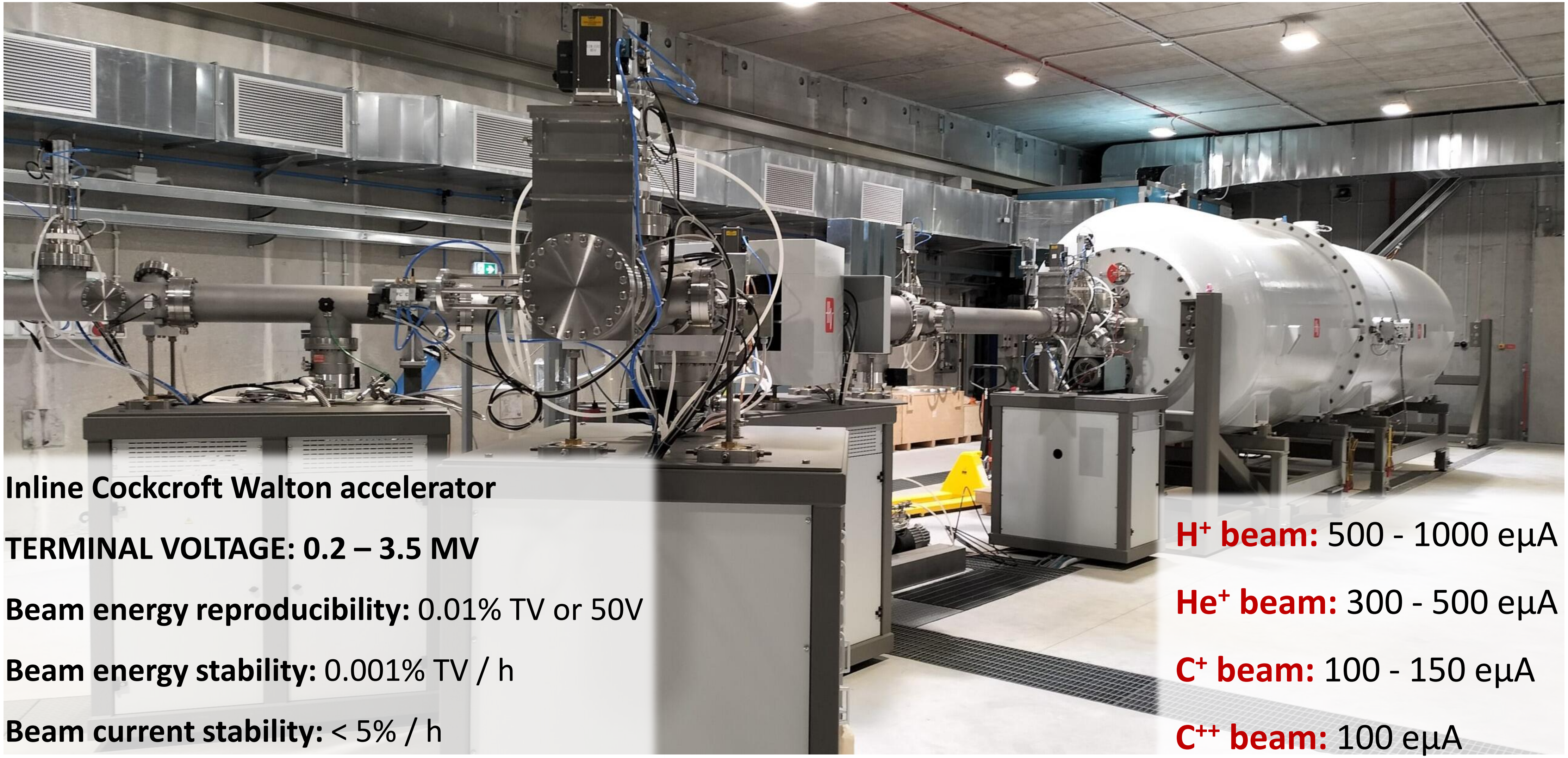


Our measurement improved the reliability in the use of primordial abundances as probes of the physics of the early Universe

The new Ion Beam Facility of LNGS



Inline Cockcroft Walton accelerator

TERMINAL VOLTAGE: 0.2 – 3.5 MV

Beam energy reproducibility: 0.01% TV or 50V

Beam energy stability: 0.001% TV / h

Beam current stability: < 5% / h

H^+ beam: 500 - 1000 eμA

He^+ beam: 300 - 500 eμA

C^+ beam: 100 - 150 eμA

C^{++} beam: 100 eμA

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LUNA @ the new **IBF of LNGS**

Measurements proposed to the PAC:

- $^{14}N(p,\gamma)^{15}O$ → already started (acc. commissioning & calibration)
- $^{22}Ne(\alpha,n)^{25}Mg$ → expected to start soon

SHADES

Scintillator-He3 Array for Deep-underground Experiments on the S-process

erc

- $^{12}C(^{12}C,p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$ → proposed for 2024 (yet to be approved)

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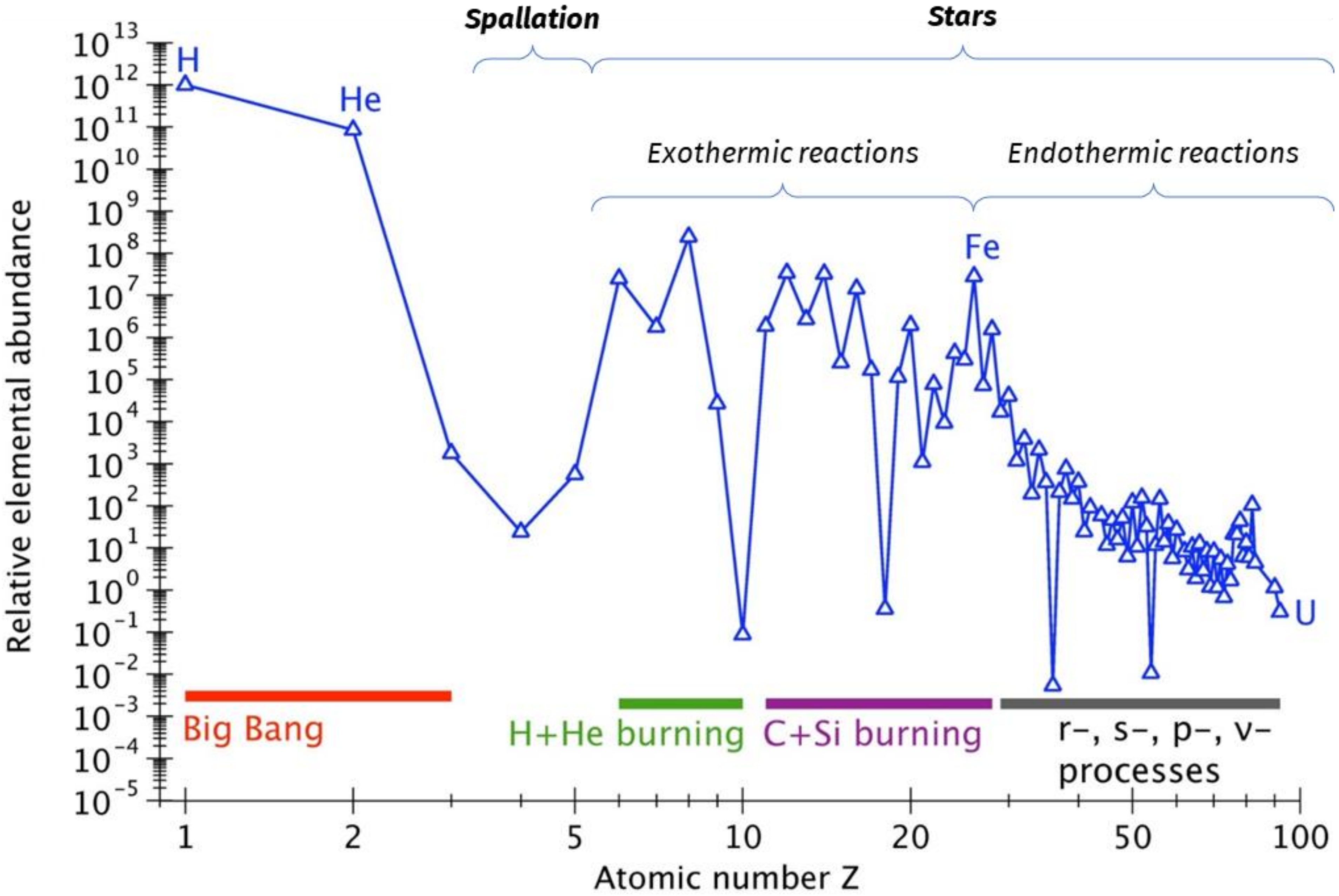
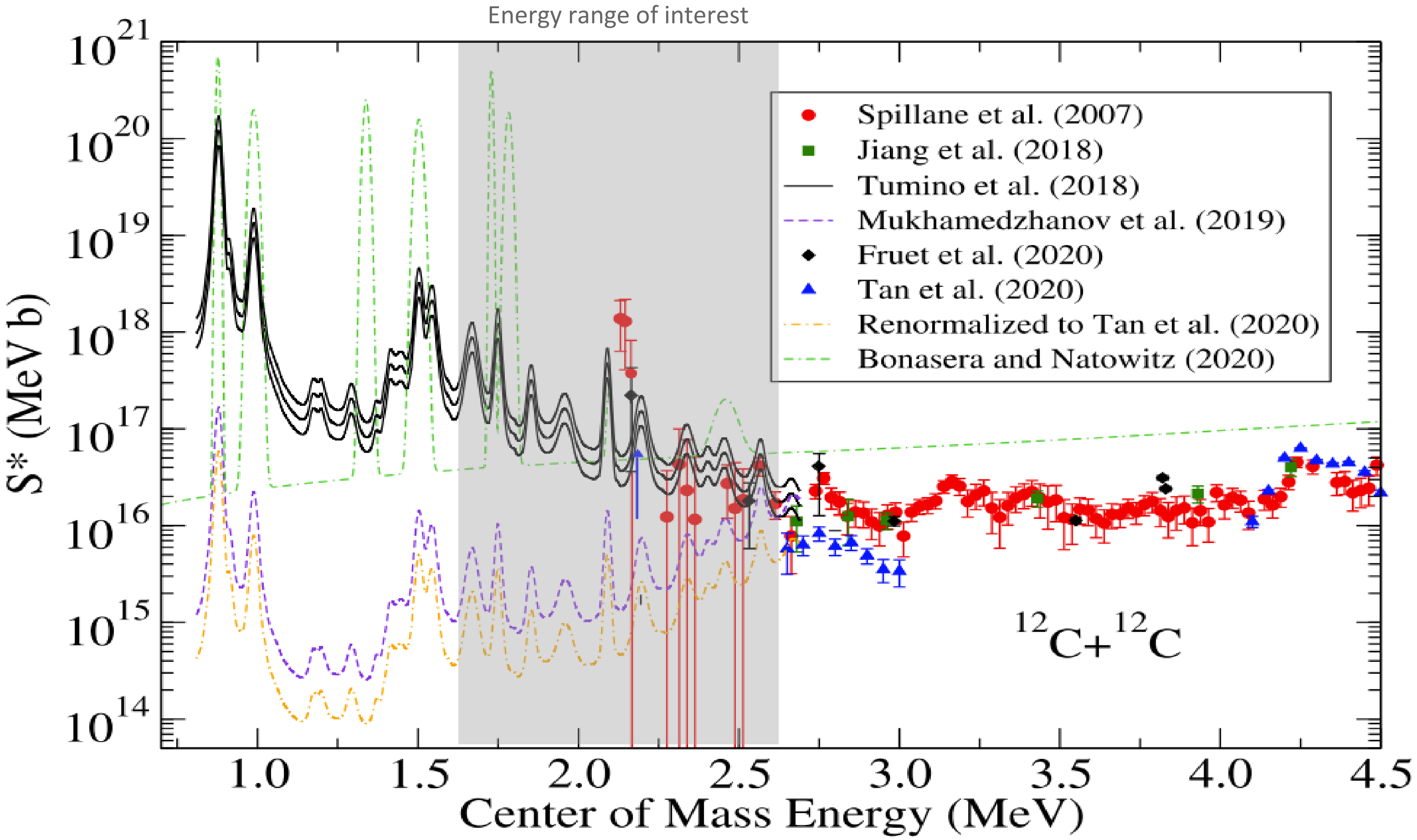

Spallation
Stars
Exothermic reactions
Endothermic reactions
H
He
Fe
U
Relative elemental abundance
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Big Bang
H+He burning
C+Si burning
r−, s−, p−, ν−
processes
1
2
5
10
20
50
100
Atomic number Z

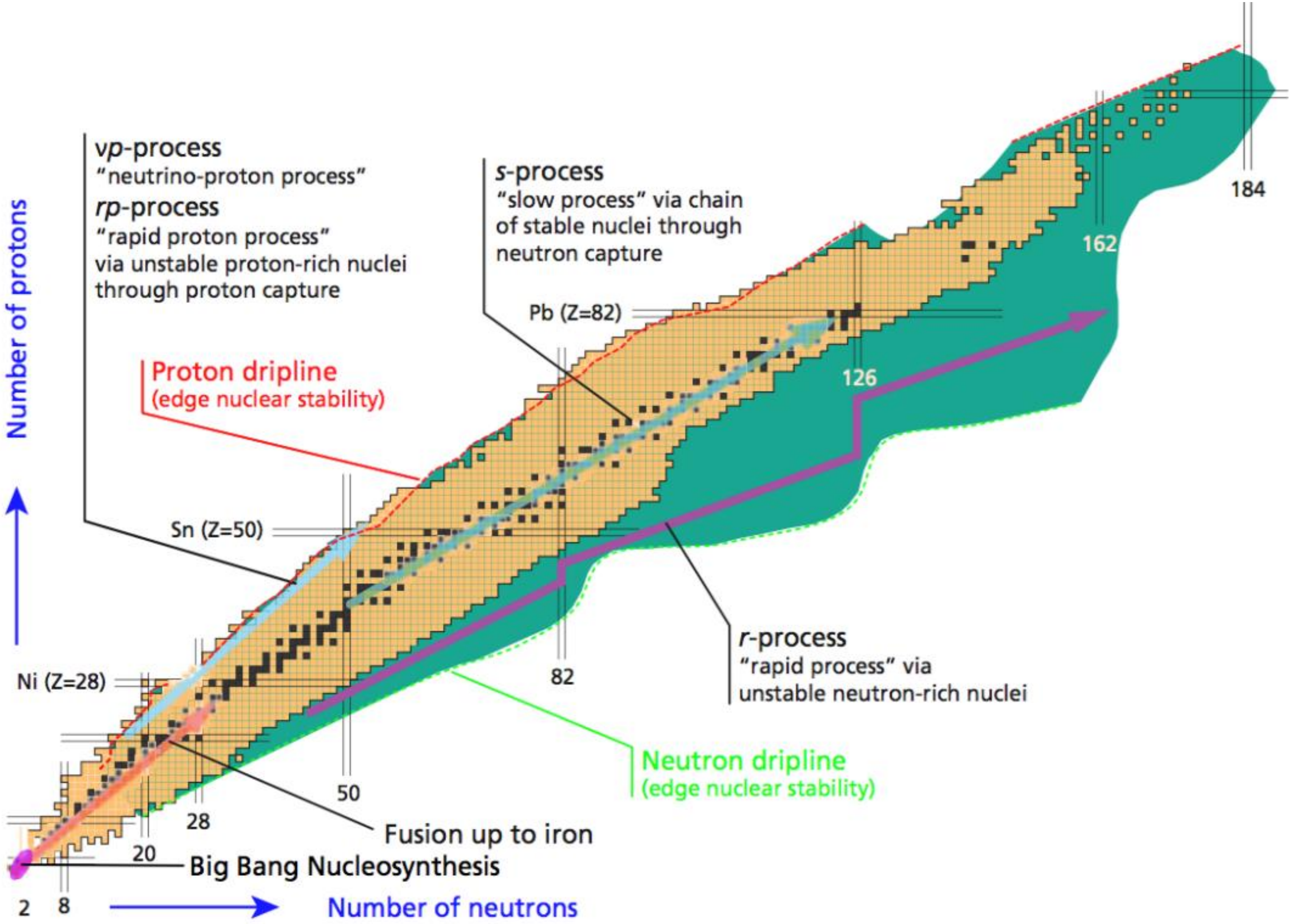
Any questions?

Backup

Discrepancies in indirect measurements



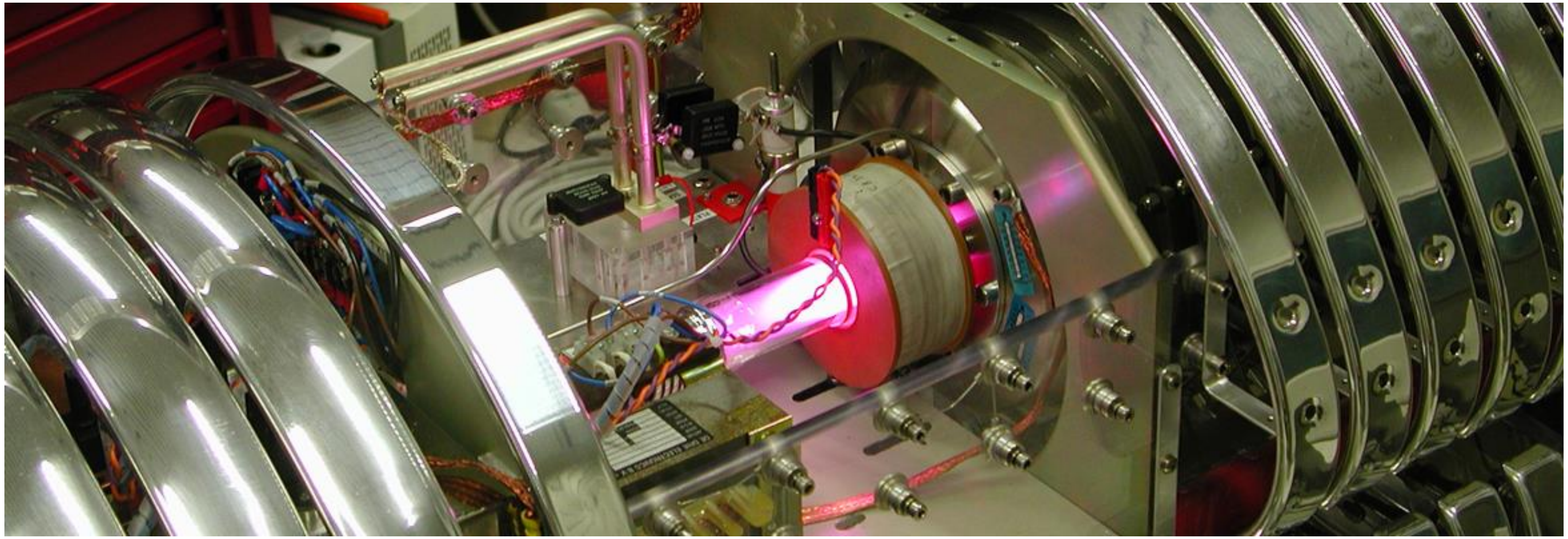
M Aliotta et al 2022 J. Phys. G: Nucl. Part. Phys. 49 010501



νp-process
"neutrino-proton process"
rp-process
"rapid proton process"
via unstable proton-rich nuclei
through proton capture
s-process
"slow process" via chain
of stable nuclei through
neutron capture
Number of protons
Proton dripline
(edge nuclear stability)
Pb (Z=82)
Sn (Z=50)
Ni (Z=28)
184
162
126
82
50
28
20
8
2
r-process
"rapid process" via
unstable neutron-rich nuclei
Neutron dripline
(edge nuclear stability)
Fusion up to iron
Big Bang Nucleosynthesis
Number of neutrons

LUNA

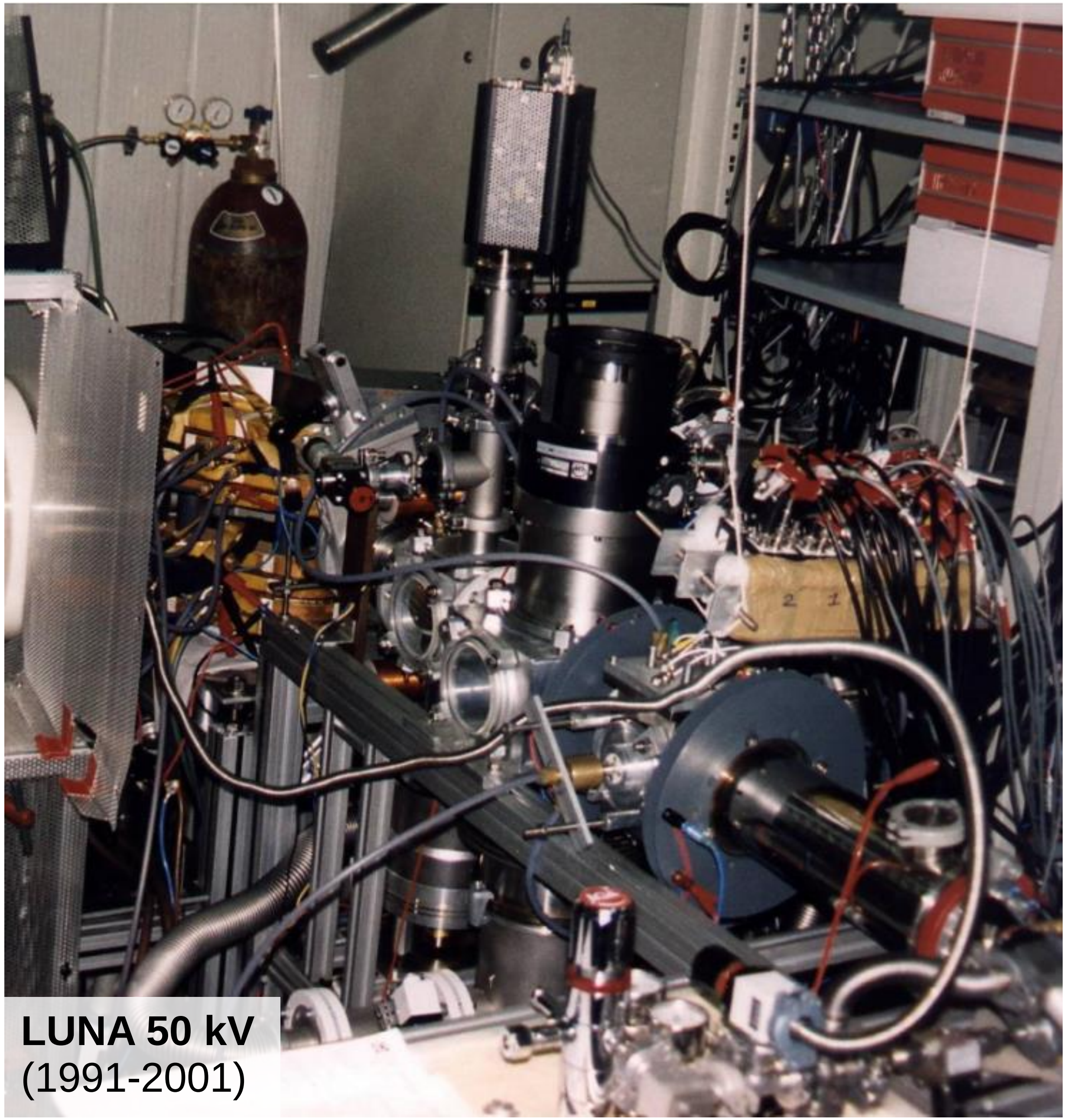
Laboratory for Underground
Nuclear Astrophysics



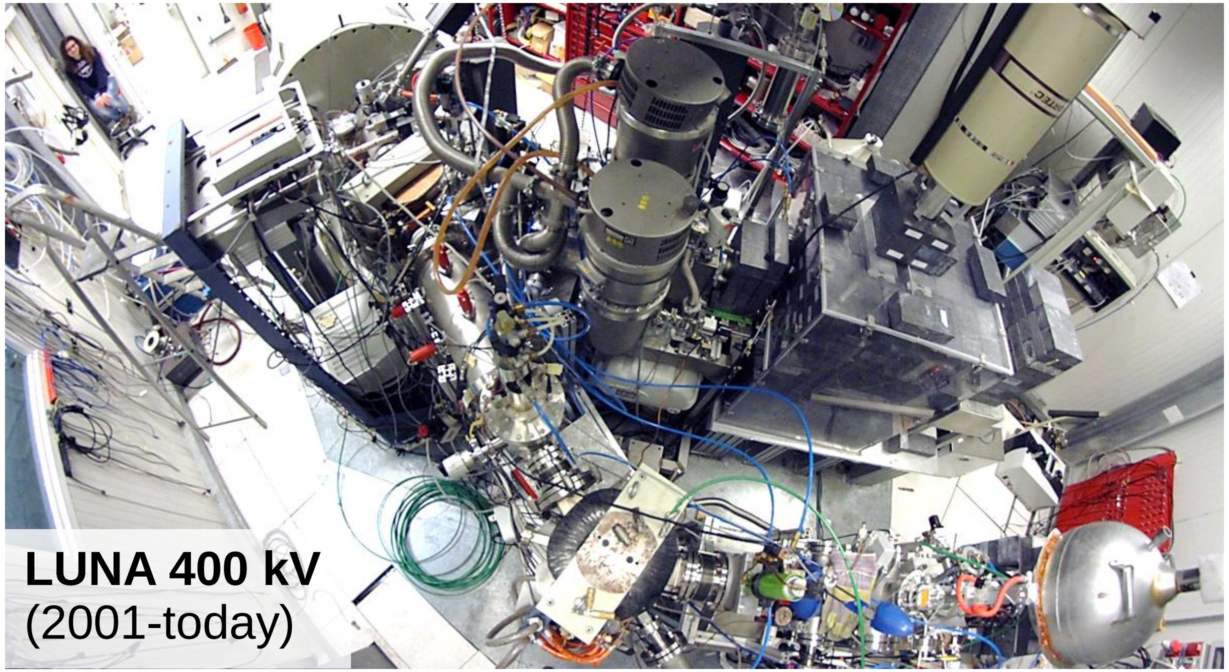
It has been the only underground accelerator for nuclear astrophysics for 25 years

Its results include

- solar physics (solar neutrinos)
- cosmological model
- big bang nucleosynthesis (BBN)
- stellar nucleosynthesis



LUNA 50 kV
(1991-2001)



LUNA 400 kV
(2001-today)

LUNA MV (LNGS-IBF)
(2023-????)

Other measurements @ LUNA 400 kV

- $^{16}O(p,g)^{17}F$ → CNO cycle → just completed
- $^{21}Ne(p,g)^{22}Na$ → NeNa cycle → just completed
- $^{23}Na(p,a)^{20}Ne$ → NeNa cycle → present
- $^{27}Al(p,a)^{24}Mg$ → MgAl cycle → future

ELDAR

Elements in the
Lives and Deaths of stARs

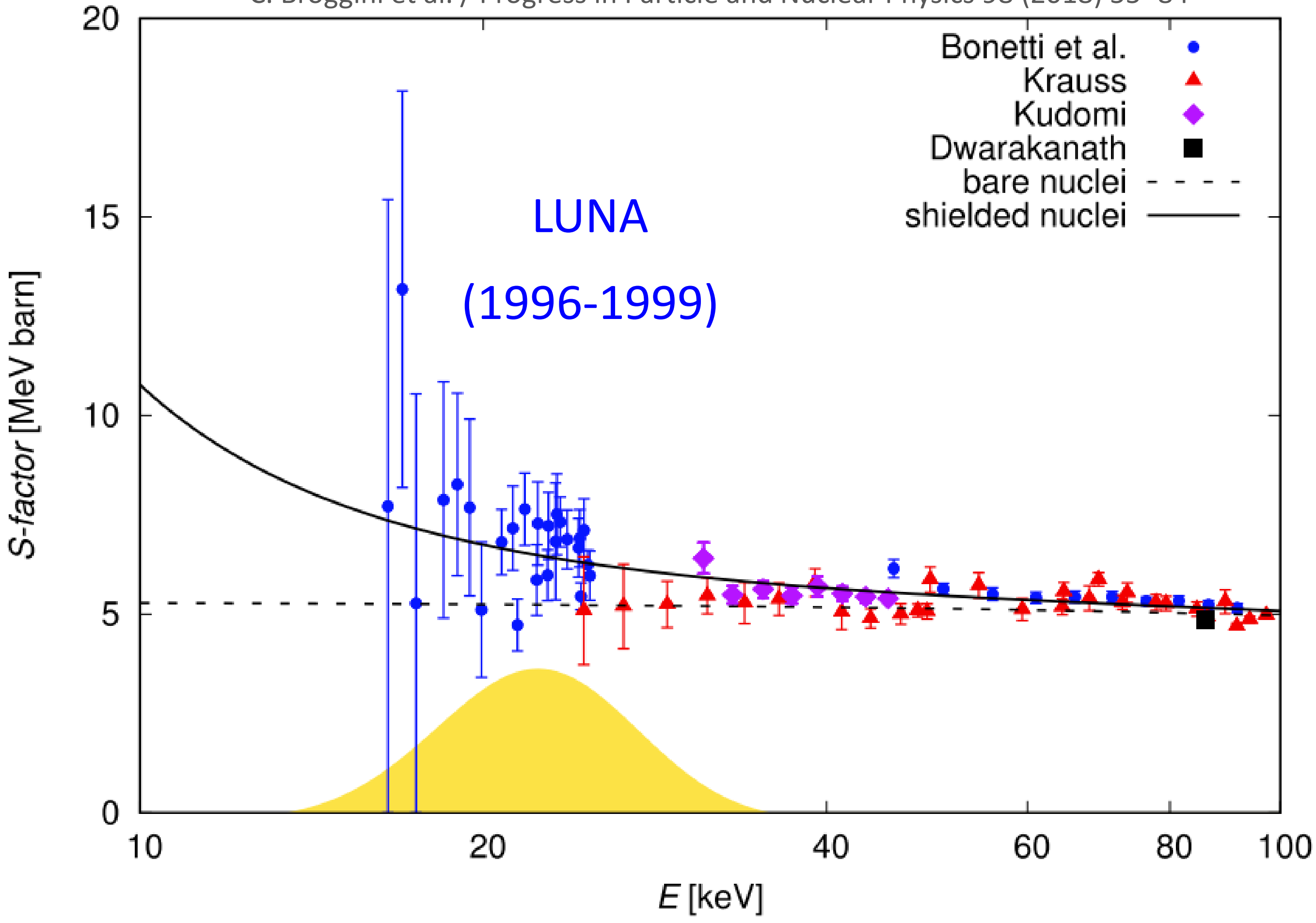
One historical measurement: $^3He(^3He,2p)^4He$

First direct measurement in the Gamow window

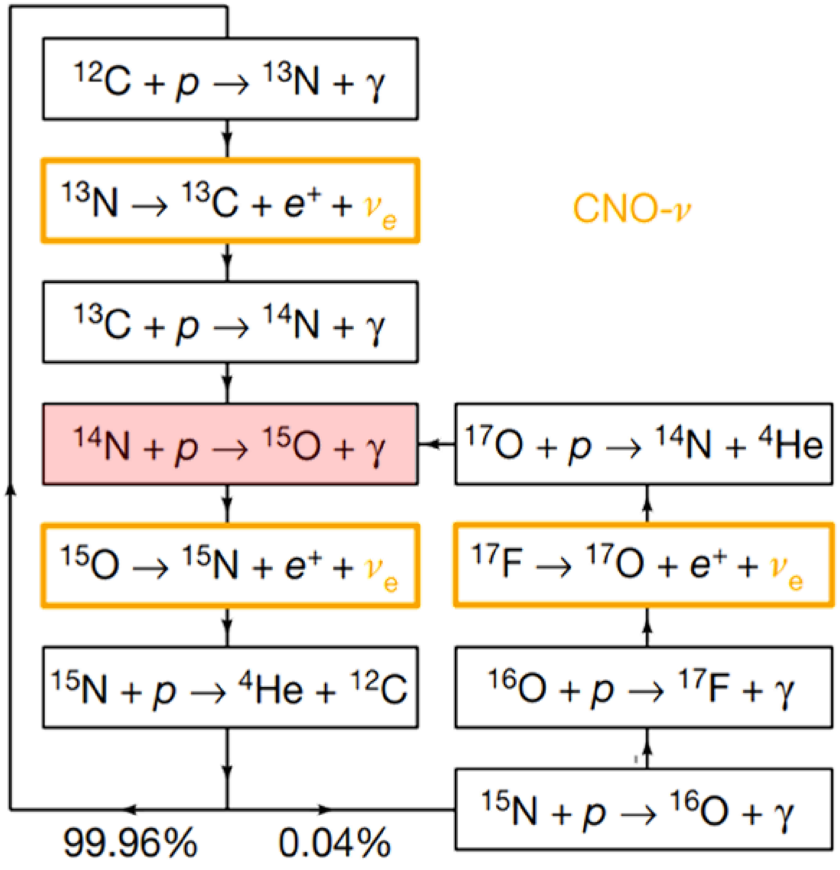
At 16.5 keV the cross section is 0.02 pb, corresponding to a reaction rate of approximately 2 events/month.

The absence of a resonance in the Gamow window allowed to discard a nuclear solution to the Solar Neutrino Problem

C. Broggini et al. / Progress in Particle and Nuclear Physics 98 (2018) 55–84



$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle



$^{12}C + p \rightarrow {}^{13}N + \gamma$

$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{14}N + p \rightarrow {}^{15}O + \gamma$

$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

$^{15}N + p \rightarrow {}^{4}He + {}^{12}C$

$^{17}O + p \rightarrow {}^{14}N + {}^{4}He$

$^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$

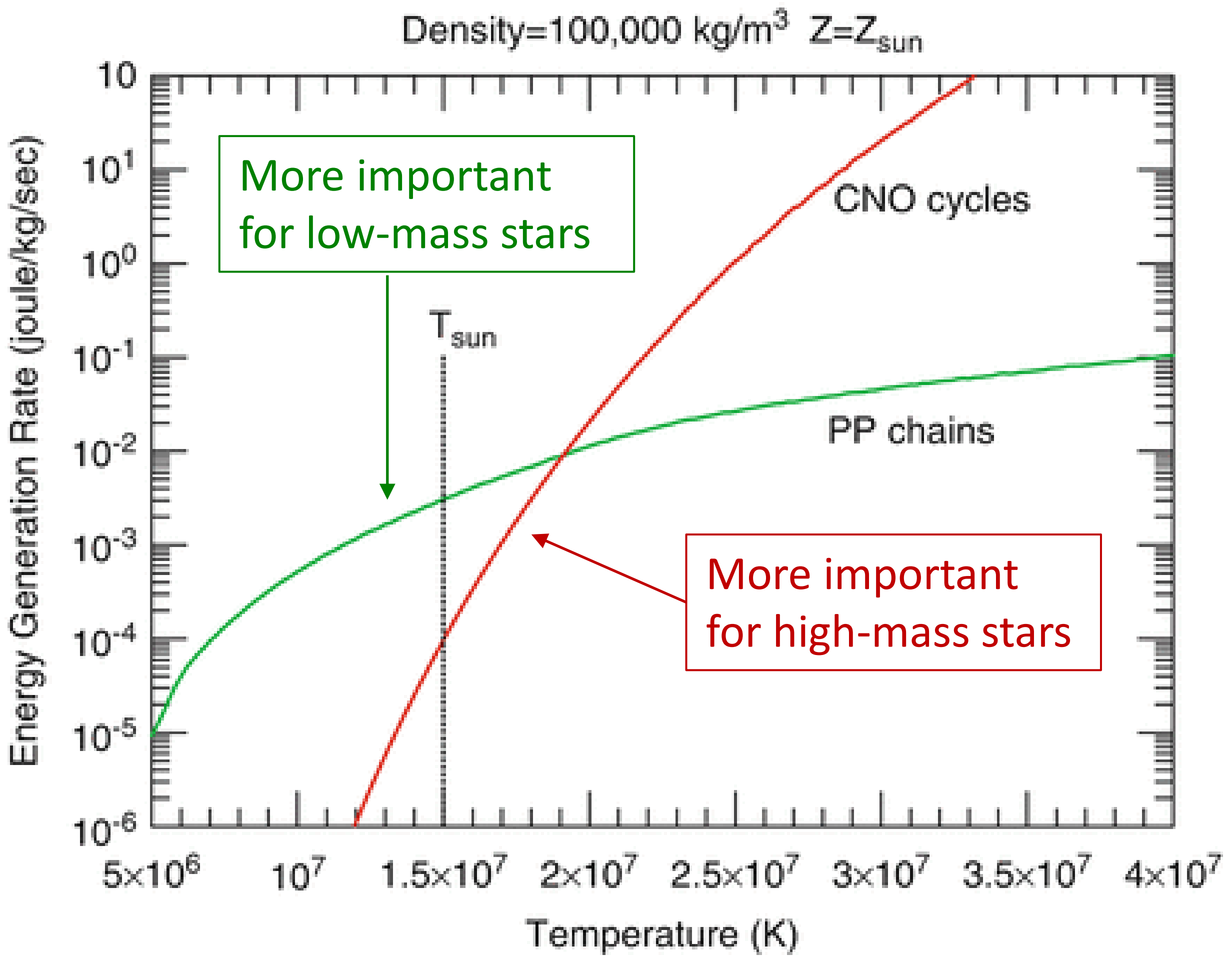
$^{16}O + p \rightarrow {}^{17}F + \gamma$

$^{15}N + p \rightarrow {}^{16}O + \gamma$

99.96%

0.04%

CNO-ν

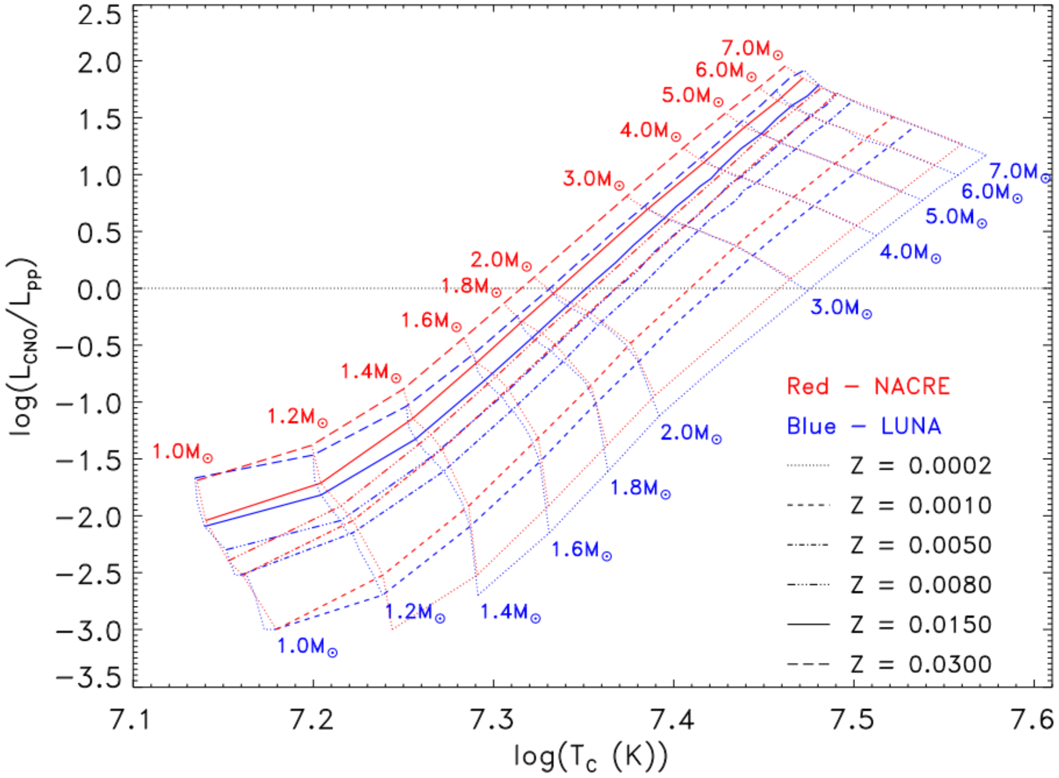


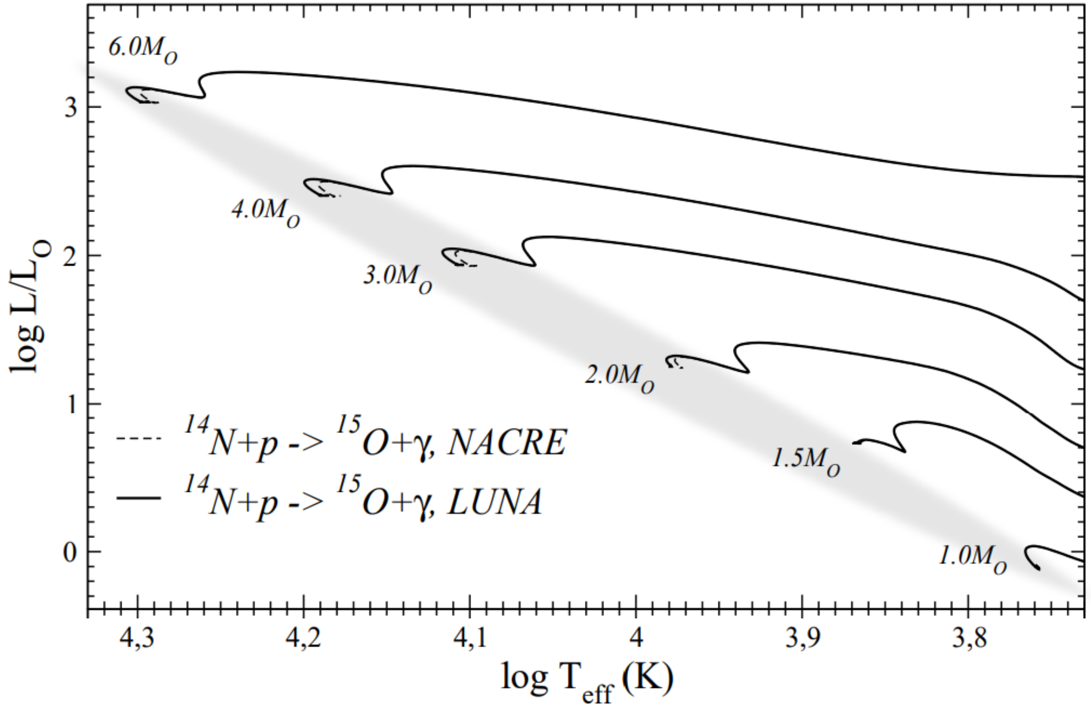
More important for low-mass stars

More important for high-mass stars

$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$: the bottleneck of the CNO cycle

•Astronomy and Astrophysics 533(0004-6361)





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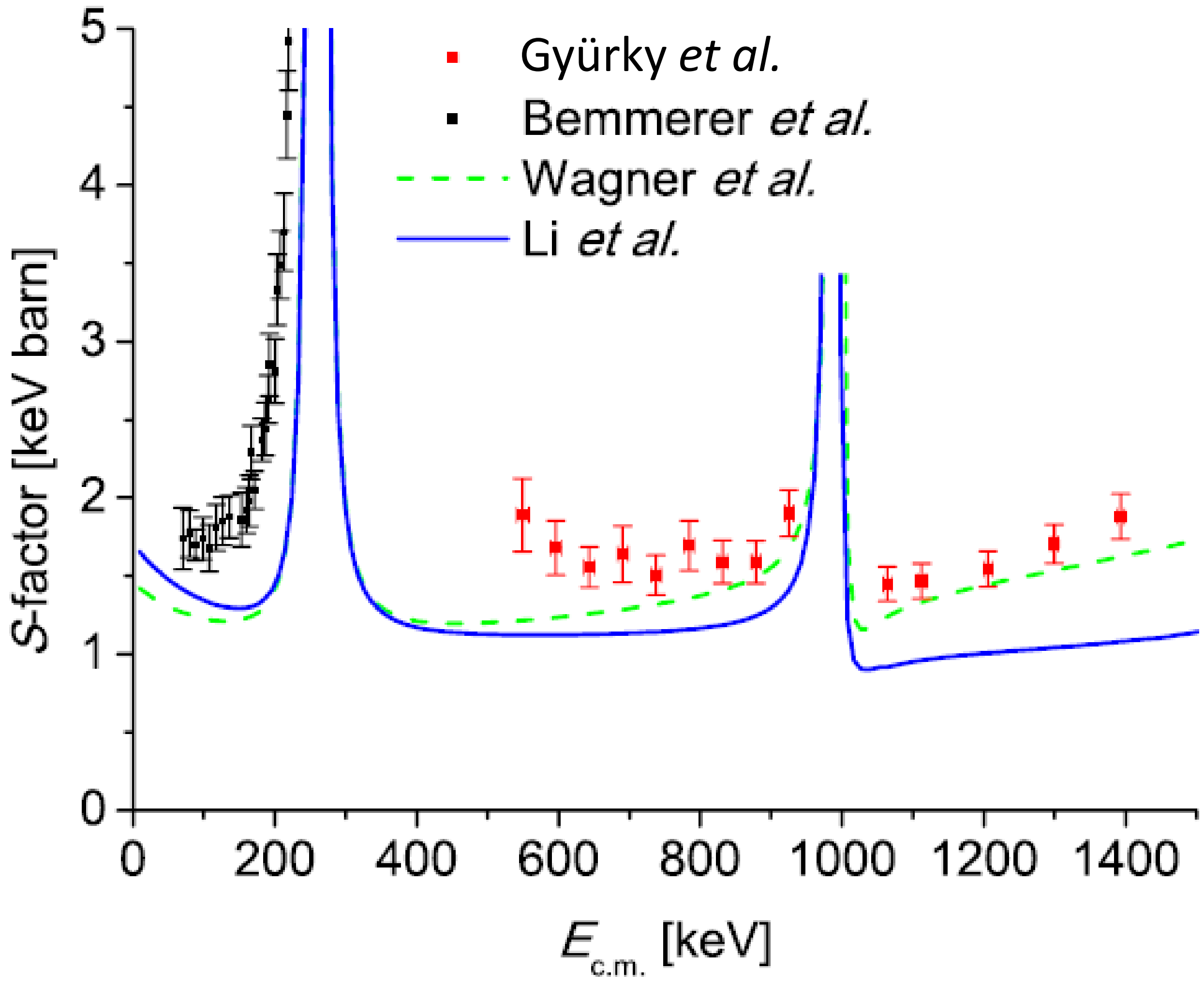
$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle



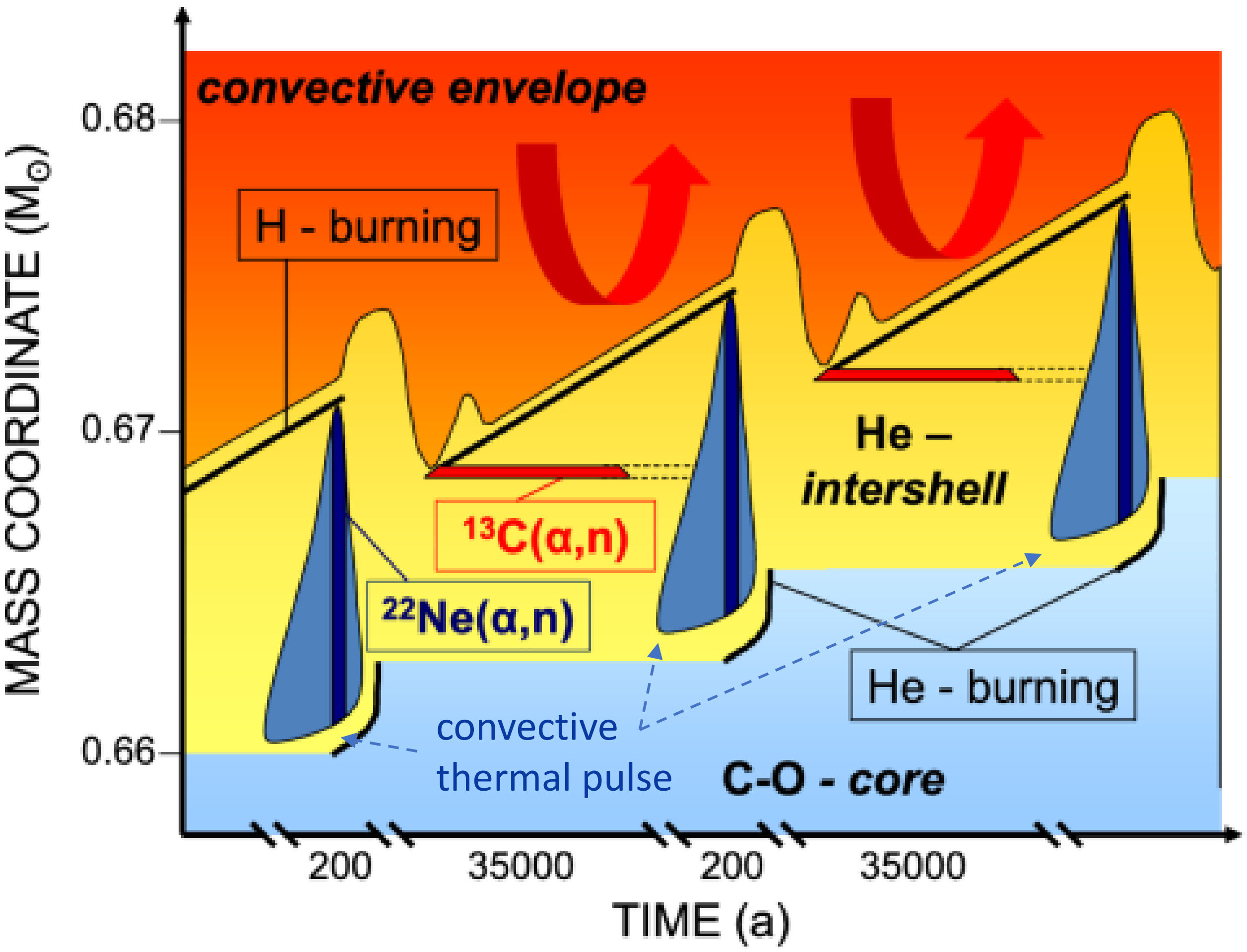
To be investigated:

- non-resonant component
- weak transitions (to ground state)
- summing-in corrections
- angular distribution

… all of this in a wide energy range!

(s-process = slow neutron-capture process)

$^{22}Ne(\alpha,n)^{25}Mg$: neutron source for the s-process



~ half the elements between Fe and Y ($56 \lesssim A \lesssim 90$) are produced via the weak s-process in massive stars ($M > 8M_\odot$)

$^{22}Ne(\alpha,n)^{25}Mg$ is a neutron source for the weak s-process